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Proceedings of the

GEOLOGISTS' ASSOCIATION

A Contribution to the Geomorphology of Central Donegal

by G. H. DURY

Received 1 October 1958; read 2 January 1959

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ABSTRACT: Much of the present drainage of central and east-central Donegal is well adjusted to the structures and outcrop-patterns of the Main Donegal Granite, the Barnesmore Granite, or the surrounding metasediments. When allowance is made for more than twenty glacial breaches, which displaced watersheds by as much as two miles and lowered them by as much as 800 feet, a simple pre-glacial divide can be reconstructed which cuts across the geological grain. Reconstructed consequent streams flowing eastward and westward from the main divide had been modified by capture and abstraction before glacial diversion took place. Sub-parallel consequents draining to the east indicate superimposition and suggest Tertiary deformation, without making clear the nature of any unconformable cover.

1. INTRODUCTION

CENTRAL and east-central Donegal includes, in an area of some 750 square miles, a belt of high ground through which the main watershed runs from north to south, and a group of wide valleys leading eastwards from the watershed towards the Foyle. Most of the area is based on the Main Donegal and Barnesmore Granites, or on metamorphic rocks regarded as mainly Dalradian. Carboniferous strata belong to the Donegal and Omagh synclines. Numerous basic dykes, of presumed Tertiary age, cross the area from south-east to north-west, at right angles to many dislocations and to outcrop-boundaries in western districts.

Altitudes range from sea-level to nearly 2500 feet. Peat, abundant at all levels, hampers the mapping of geology and landforms, but glacial drift is less bulky than might be expected from a former complete cover of ice. Compact highland occurs on the central part of the Main Donegal Granite, and on the Barnesmore Granite and the adjacent granulites, while belts of quartzite form lines of high hills.

The belt of highest summits, the present main watershed, and the reconstructed pre-glacial watershed all run obliquely across the south-west to north-east trend of structures and outcrops. Several east-flowing trunk streams are markedly discordant to structure. Although the geology is accurately reflected in many stream-reaches, and in many minor—and some large—elements of relief, traces have been preserved of early landscapes which were not dominated by subsequent features. The existing stream-net has developed from an array of east-flowing consequents.

Field-mapping has been applied to a larger area than that discussed here, providing the basis for observations on streams draining northward, westward and southward from the main watershed, on the terrain of Carboniferous outcrops, on erosional platforms, and on signs of rejuvenation in the valleys of the Finn and other rivers. Full discussion of these matters, however, is reserved for later occasions.

Relief, structure and morphology are shown separately, for the northern and southern parts of the area, in Figs. 1–3 and 4–6. The morphological maps rely chiefly on continuous lines to show breaks of slope, with hachures indicating steep hill-sides and valley-walls, and heavy ticks marking waterfalls, rapids and rejuvenation-heads in general; the maps are not intended to give a full representation of the results of field-work, but merely include features relevant to the present paper.

Place-names used in reference are almost exclusively the names of physical features, since most settlement-names refer to single dwellings or hamlets. Many feature-names, simple and descriptive in the Gaelic, reduplicate themselves throughout the area, and additional detail is cited to aid identification where such names are used. The initials and abbreviations on the maps of structure and morphology are explained in the text, unless the relevant names appear in full on the maps of relief.

Previous work on morphology is largely confined to the detailed glacial studies of Charlesworth (1924), and to descriptions of certain glacial breaches (Dury, 1957, 1958). Since the geology is, in part, well documented by recent papers, with more known to be in the press or in preparation, no attempt will be made to outline the geology of the area, but references will be inserted in the following text.[1]

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[1] The comprehensive account of the Main Donegal Granite and its envelope by Pitcher & Read (1958) was published while the present paper was at the press. The subsequent text does not include cross-references to this account, which is, however, of prime structural importance, and which includes a detailed map of the Granite and its borders.

2. MORPHOLOGY AND STRUCTURE OF THE MAIN WATERSHED

(a) Northern Part

(*i*) *Errigal–Muckish Ridge and Upper Calabber Valley*. The northern part of the high ground includes the Errigal–Muckish ridge and the central knot of high ground on the Main Donegal Granite (Figs. 1–3). Muckish (2197 feet), Errigal (2466 feet), Aghla More (1916 feet), and Aghla Beg (1860 feet) testify to the strength of the Ards Quartzite which underlies them. Drainage towards the coast is well adjusted to the geology of the Falcarragh syncline (Pitcher & Cheesman, 1954, fig. 1), although moraines cause minor diversions (Charlesworth, 1924), while stream-courses in the extreme north-west accord well with the outcrop-pattern of a synclinal area mapped by McCall (1954). The lower south-east flank of the Errigal–Muckish ridge is cut in Ards Black Pelitic Schists, while the floor of the wide Calabber Valley is underlain by weak schists of the Creeslough group (McCall, 1954). Drainage within five miles of the head of Sheep Haven is almost wholly adjusted to the strike of the steeply inclined schists, cross-connecting reaches running north-west or south-east being probably associated with Tertiary dykes, with master joints, or with both. Ice in this locality moved northward at glacial maximum, but extrusion-flow at the base of the sheet may have been responsible for much selective erosion. In the basins of the Faymore and Duntally, on either side of Creeslough, it seems impossible to reconstruct a drainage-pattern significantly different from the present; if such a one existed pre-glacially, it has been obliterated.

The Errigal–Muckish ridge has been deeply breached by transfluent ice (Dury, 1957). The crestal watershed south-west of Muckish was displaced by about half a mile (Fig. 3), the sill of Muckish Gap being ground down through some 400 feet; a valley-head between Muckish and Aghla More was converted to the remarkable perched basin of Lough Aluirg; a pre-glacial col on the site of Altan Lough, with a sill at about 800 feet, was punched through and replaced by a deep basin, where the depth of gouging can hardly be less than 400 feet and may well exceed 500.

Altan Lough now receives from the flanks of Dooish a stream which, in pre-glacial times, fed the Calabber (Fig. 3). A second head of the pre-glacial Calabber probably rose in the col on the site of Altan Lough, and a third in the col between Dooish and Errigal. The Owenbeg, which now drains from this third col into the Calabber, is strictly aligned on the marginal sheets of granite and pegmatite which borders the neatly exhumed, wall-like edge of the Main Donegal Granite (Fig. 2). The Owenwee, draining into Poisoned Glen, is similarly adjusted. Each stream, incised into an old valley-floor, may be regarded as a pre-glacial subsequent, but it is difficult to estimate the effects of local glacial erosion or of the lowering

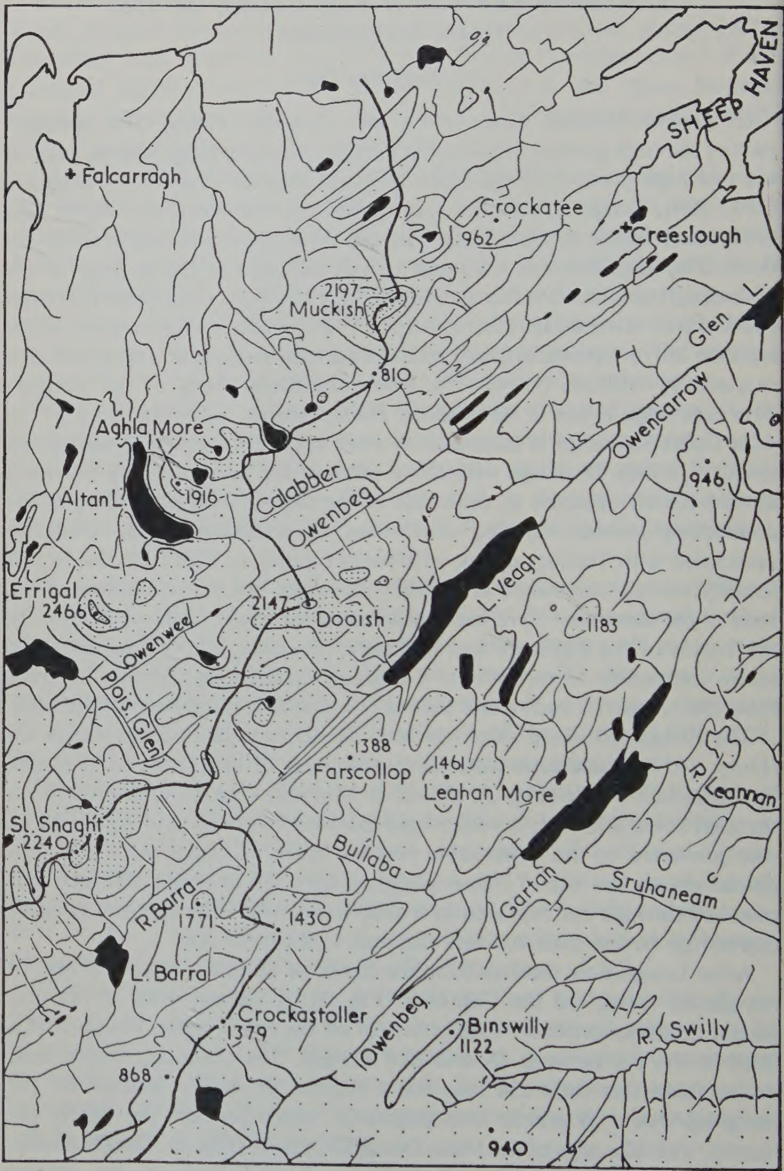

Fig. 1. Northern part of the main watershed: relief and location. Key as in Fig. 4

of local base-level which accompanied gouging in the Calabber Valley and in Poisoned Glen. The two old valley-floors, uniting at about 900 feet in a rock-based col, slope gently down from the line of the pre-glacial watershed (Fig. 3).

The restored watershed of the pre-glacial upper Calabber bounds a broad valley-head terminating in ample cols at 800–1000 feet. The outlet was along the route still followed by the Calabber towards the east—on to the granite through a wide, shallow gap with erosional benches on either side—by a discordant reach which is one of the most northerly relics of original drainage towards the east.

(*ii*) *Derryveagh and Glendowan Mountains.* The central mountain knot on the Main Donegal Granite is often called the Derryveagh Mountains. Strictly speaking, however, the Derryveagh Mountains lie north-west of the Gweebarra–Owencarrow line (Fig. 1), while the block south-east of that line and south-west of the upper Bullaba forms the Glendowan Mountains. There seems to be no distinctive name for the hill-mass which includes Farscollop, Leahan More and the lesser granitic summits between Lough Veagh and Gartan Lough.

Most streams in this whole mountainous area are aligned on faults, crush-belts or Tertiary dykes. The dykes have not all been mapped, and no more than a small selection of those mapped is indicated by the heavy dotted lines in Fig. 2, where it can, however, readily be seen that numerous streams run along, or parallel to, the dykes indicated, suggesting widespread adjustment to the weak outcrops of dolerite or to parallel joints which have not been injected. With drainage almost entirely adjusted to some kind of structure, and by inference subsequent, it becomes difficult to reconstruct early drainage-patterns. Nevertheless, when allowance is made for the effects of glaciation, it becomes possible to restore a drainage system which was in part discordant.

Glaciation of the mountain knot included, in addition to general scour of the summits, the formation of corries and the excavation of troughs. A set of large corries occurs at the head of Poisoned Glen, where the crest of the Derryveagh Mountains descends gently between Dooish and Slieve Snaght. Two corries facing the south-west are aligned on planar structures in the granite, while two facing north-west follow the strike of the Tertiary dykes, which are numerous and close-set within Poisoned Glen. The two north-west-facing corries connect through narrow trenches at their heads with opposing corries at the heads of short hanging valleys leading south-east. Charlesworth (1924) has already interpreted the trenches as eroded on the line of dykes by ice which entered the Poisoned Glen from above. Glacial transfluence is not necessarily implied, for the headwalls of two additional south-east-facing corries, respectively half a mile south and one mile east of Slieve Snaght, have been scoured into remarkable smoothness.

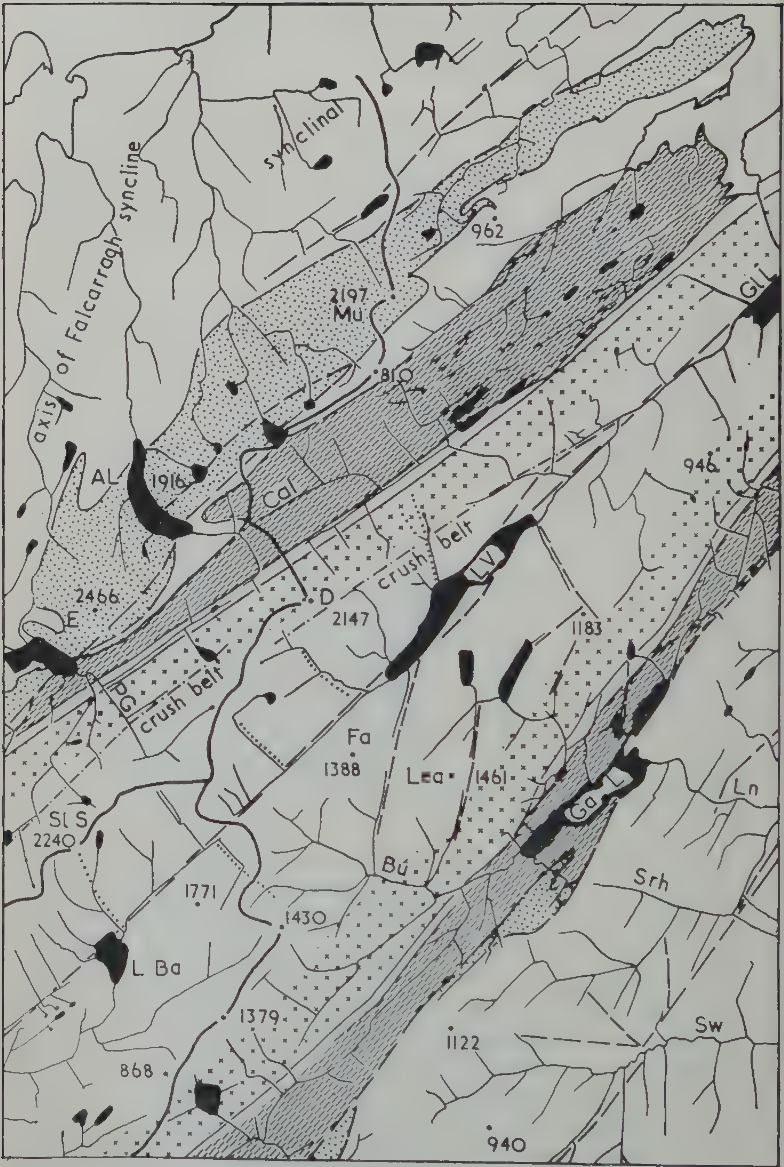

Fig. 2. Northern part of the main watershed: some geological distributions. Key as in Fig. 5; see text also

Ice appears to have slid from the summits into all available depressions.

Poisoned Glen is essentially a subsequent valley, guided by Tertiary dykes and opened by a pre-glacial river. The main pre-glacial watershed encircled its head (Fig. 3). By contrast, the trench on the Gweebarra–Owencarrow fault-line seems in its present form to be largely of glacial origin. The pre-glacial Bullaba appears to have risen north-west of the fault-line, the fault-guided streams of pre-glacial times being accordingly reduced in length (Fig. 3).

The post-glacial watershed between the Barra and the Owenveagh (the head of the Owencarrow above Lough Veagh) crosses the floor of Barra Pass, on drift, at less than 800 feet, and continues southwards up the flanks of the Glendowan Mountains to Croaghacullin (1430 feet, Fig. 1). Barra Pass connects with the Bullaba Valley through a smoothly moulded gap south-west of Farscollop—a gap apparently far too wide to represent an extreme pre-glacial valley-head, while the summits of the Glendowan Mountains consist of integrated gentle slopes—broad subdued divides and wide shallow valleys—which lead eastwards towards the upper Bullaba. These summit-surfaces (very well seen from high ground to the north) lie almost everywhere above 1000 feet; they seem to be the remains of an old land-surface, which was worn down under the control of the Bullaba and cut through by that river on rejuvenation. Both the old land-surface and the Bullaba which drained it must be antique features.

The upper valley of the Barra, and almost the whole of Glenveagh, are products of glaciation. High ground closes in sharply about the head of the Barra, even though the whole side of Moylenanav (1771 feet) and the end of the contraposed spur (Crockbrack) have been shorn away. The pre-glacial divide in Fig. 3 runs along Crockbrack, through a summit more than 1300 feet high, over the site of the vertical wall at the end, and directly to Moylenanav; this restoration seems irresistible when the ground is observed from high viewpoints on the north. In Glenveagh above Lough Veagh, streams from the Derryveagh Mountains plunge down from heights of 800 to 1000 feet. The narrow trough, with its precipitous walls abruptly truncating the high summit-surfaces, shows no sign of an ample pre-glacial valley comparable to that identified on the Bullaba. The pre-glacial watershed (Fig. 3) has been drawn across upper Glenveagh directly to Farscollop, and thence to Leahan More across a second fault-guided valley which, deeply eroded but still quite narrow at its northern end, may fairly represent the pre-glacial condition of Glenveagh.

According to this interpretation, pre-glacial headstreams which came off the Derryveagh Mountains near Barra Pass were first diverted along the Gweebarra–Owencarrow fault-line, and then collected by the Bullaba, which thus becomes another remnant of easterly drainage. Although the uppermost reaches of the pre-glacial Bullaba may have been generally

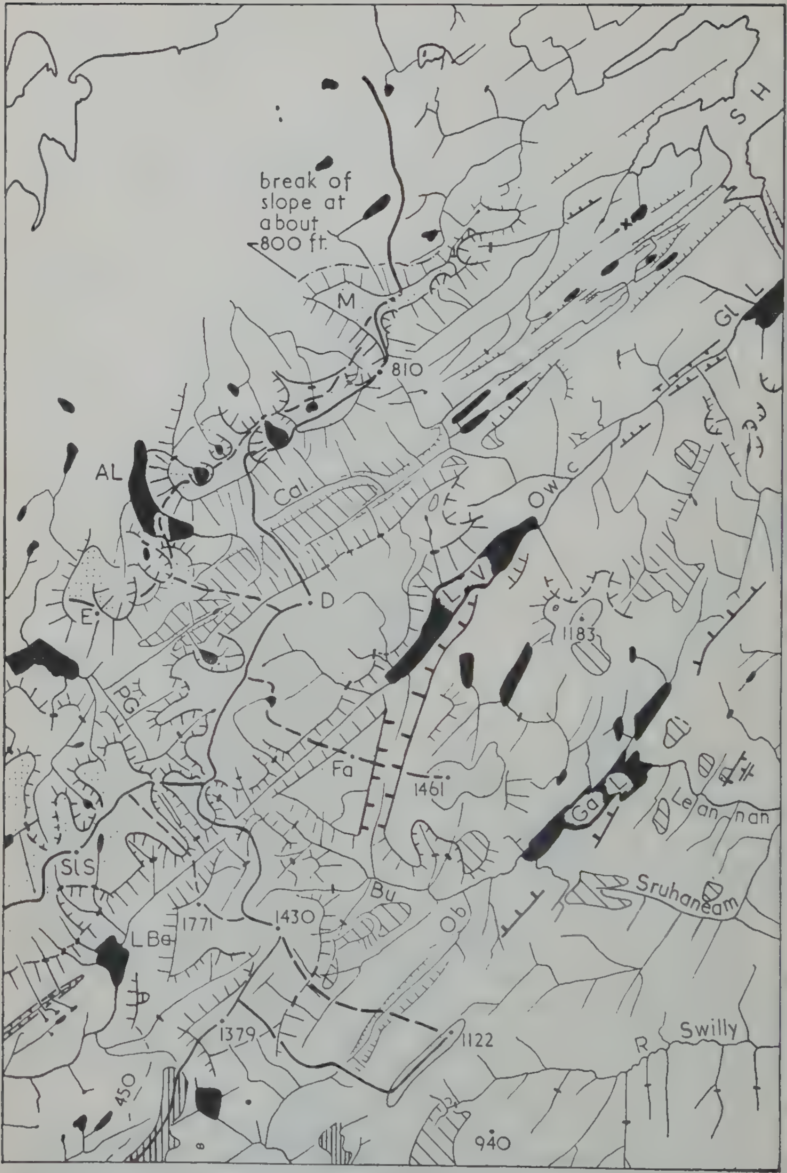

Fig. 3. Northern part of the main watershed: some morphological distributions. Key as in Fig. 6. Erosional platforms at high levels are not distinguished

adjusted to structure, the extreme head of a discordant stream may perhaps be found on the north flank of Croaghacullin.

If the heads of the Barra Valley and Glenveagh are glacial breaches, punched through lateral watersheds by basal ice, no more than modest progress is implied for the subsequent Barra and Owenveagh which were developing along the fault-line. Even today, however, the Gweebarra itself fails to follow the dislocation for some miles below Lough Barra, wandering instead across platforms cut in the granite. It is true that the fault-line is now marked by a narrow gash occupied by another Owenwee, with which the Gweebarra eventually unites, but the pre-glacial Gweebarra seems to have flowed right across the dislocation, in the direction marked by a heavy arrow in Fig. 6, passing through a broad col on the far side. Neither here nor in upper Glenveagh are there signs of wide pre-glacial valleys developed along the fault.

(*iii*) *South-eastern Side of the Main Donegal Granite.* As on the north-west, the Main Donegal Granite on the south-east is bordered by weak schists, and these in turn by quartzite (Figs. 2, 5). Although identical symbols are used on the annexed maps, the two series of metasediments are distinct, meeting in a mechanical junction at the north-east extremity of the granite (Pitcher & Cheesman, 1954). The schists on the south-east include members of the Glendowan Group and the Fintown Flags; the quartzite, little in evidence near Gartan Lough, broadens and rises towards Lough Finn, reaching 1961 feet on Aghla Mountain which is cut in the Slieve Tooey Quartzite. Marginal sheets of granite and pegmatite on the south-east side of the granite exert little influence on stream-direction, possibly because the granite, less contaminated by admixture, is weaker than on the north-west. Very many subsequents are aligned on the schists, while the sites of Gartan Lough and Lough Finn are traversed by faults.

The Leannan discharges from the lower end of Gartan Lough, flowing eastwards across the strike—including the strike of a fault-line marked by small scarps (Fig. 2). The upper Sruhaneam, also flowing eastwards, rises in a broad flat-floored col which connects it with the upper end of Gartan Lough and is aligned on the upper Bullaba. Both west–east reaches appear to be relics of an early drainage-pattern. The upper Swilly, farther south, is a clearly superimposed and less modified stream.

That Owenbeg which drains towards Gartan Lough from the south-west flows over schists between Crockastoller and Binswilly. Its valley, choked with coarse drift which the river has deeply trenched, was identified by Charlesworth (1924) as the spillway for an ice-dammed lake located south-west of Binswilly in the valley of the Cummirk. Parallel to the Owenbeg, and three-quarters of a mile to the north-west, another Owenwee flows north-east in a valley cut in granite. Although the col at the head of the Owenwee is but slightly higher than that at the head of the Owenbeg, it seems not to have carried spillwater, but at both places the pre-glacial divide has probably been breached. The present divide runs across bog in wide, shallow troughs, whereas both valleys close in lower down, and broad gentle slopes run south-westwards from the flanking crests. The pre-glacial divide in Fig. 3 is drawn directly from Croaghacullin to Binswilly, crossing the Owenwee Valley at the head of a well-marked shelf at 800–900 feet, behind which the valley-wall curves inwards. Glacial lowering and displacement of the divide in these two valleys constitutes two of the few identified cases of breaching of minor watersheds.

(b) Southern Part

(*i*) *Lough Finn and its Surroundings.* The present watershed north of Lough Finn approaches the edge of the Main Donegal Granite at a very low angle, running for six miles along the subdued crest of Gubbin Hill (Figs. 4, 5 and 6). Remnants of an erosional platform at about 800 feet occur on Gubbin Hill and on summits of schist and quartzite to the east. In the west, feeders of the Gweebarra drain the glacially modified and dissected relics of lower platforms which, as shown by generalised contours in Fig. 6, terminate landward at something over 200 feet and somewhere in the range 400–500 feet.

Dislocations bounding the outcrop of Slieve Tooey Quartzite are probably thrusts rather than high-angle faults (Pitcher & Cheesman, 1954; Akaad, 1957). Outcropping near the base of steep slopes, they are not followed by streams. High-angle faults are reflected in part by narrow trenches, such as that drained by the Glenleheen Stream, and in part by steep rock-faces, as in the fine fault-line scarp with little lakes at its foot west of the summit of Aghla Mountain. Both the Finn and the Cummirk break across the quartzite, being broadly transverse to local strikes as far as their confluence (Fig. 5). The combined stream, crossing a belt of dislocation where the strike changes by 90°, is adjusted for some distance, but later becomes discordant again. Parts at least of the upper Finn and the Cummirk represent discordant streams flowing towards the east, although difficulties arise in explaining their relationship to the 800-foot platform.

Glacial breaching has modified the drainage system in at least three places (Figs. 6, 8). The trough containing Lough Finn is far deeper and steeper-sided on the south-east than on the north-west, where valley-side benches are well preserved; similar benches run up the valley (that of the Shallogan) which leads south-west from Lough Finn, extending into the present basin of the fault-guided Glenleheen Stream. The benches in upper Glenleheen and the west-facing corries on Aghla Mountain represent pre-glacial valleys tributary to the Shallogan, so that the fault-line trench in Glenleheen is classed as a feature of glacial erosion, the pre-glacial watershed being drawn across it to Croaghleheen. Since this locality lay west of

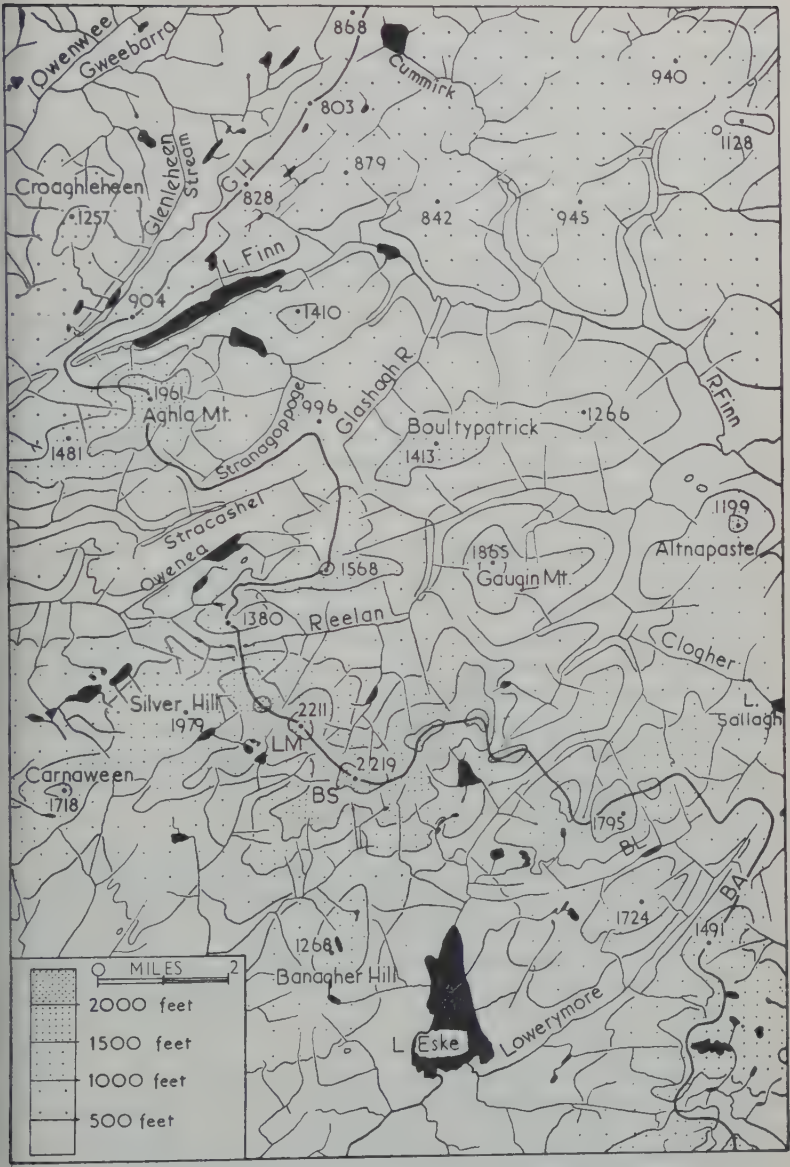

Fig. 4. Southern part of the main watershed: relief and location

the main ice-shed, ice moving across it to the north-west (Charlesworth, 1924), the inferred displacement of the divide towards the south-west presents no great difficulty, although the development of the fault-line trench must be ascribed to plucking, extrusion-flow, or both combined.

A second breach, at the head of Lough Finn, is indicated by severe shearing on the side of Aghla Mountain and by the pattern of minor streams. Although Aghla Mountain was completely overridden from the east, basal ice seems to have moved south-west along pre-glacial strike valleys, eroding a basin between the bastion of quartzite and the low wall of granite. Unlike Altan Lough, Lough Finn lies to one side of the pre-glacial divide, and has been able to attract post-glacial drainage to its south-west end. The pre-glacial watershed in Fig. 6 happens to cross the valley-bottom where a well-known depositional feature is located—a steep bank of washed debris, usually called a recessional moraine but better classed as a kame; the present watershed between the extreme head of the Finn and the trunk of the Shallogan crosses the schist belt on a second but less-well-defined kames and a former lake-basin between the two kames has been obliterated by peat and by drainage towards Lough Finn (cf. and cp. Charlesworth, 1924).

The third breach is a deep col on the south-east side of Lough Finn, where a small ribbon lake (Lough Muck) collects drainage from Aghla Mountain and discharges towards the Stranagoppoge (St. in Fig. 6). The col, now at 600–700 feet, was deepened by ice moving north-west, the basin of Lough Muck resembling that of Lough Finn in being excavated where ice was constricted by converging walls. Shoulders on the side of the col suggest deepening by more than 300 feet, and Lough Muck now receives streams which once ran directly to the Finn. Faint signs of an old valley-floor sloping down to the Finn from a height of 800 feet or more can be seen on the hill-side south of Lough Finn, particularly when the site is viewed from high ground on the far side.

The pre-glacial landscape about Lough Finn resembled that in the upper Calabber Valley, with broad cols at 500–600 feet and opposing streams roughly equal in erosive powers. Although the pre-glacial watershed had been approximately stabilised by lengthy processes of stream-competition and differential erosion, there is evidence of westward encroachment by the Finn system in the interrelationship among the Finn, the Gweebarra, and the 800-foot platform.

The pre-glacial Gweebarra was probably extended across inshore sediments and wave-cut benches as base-level fell, its original discordant character being thus easily explicable. The Finn, on the other hand, was superimposed at some higher level than 800 feet, and discordant items in its uppermost reaches are very difficult to explain if the 800-foot platform is entirely wave-cut. Fragments of this platform occur quite widely in

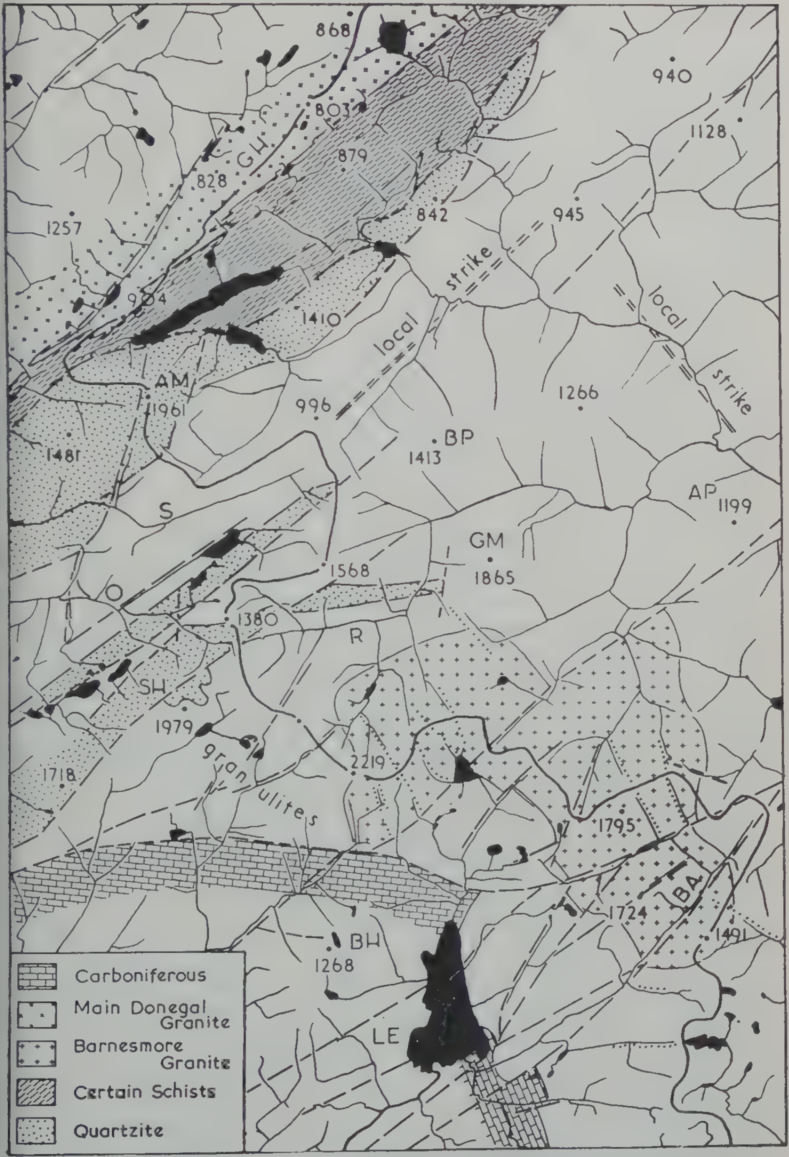

Fig. 5. Southern part of the main watershed: some geological distributions

Donegal, and it does seem to be in part marine, but broad expanses of plateau in the range 800–900 feet, between Lough Finn and Gartan Lough, seem to represent a low coastland reduced under the control of the 800-foot sea. A long stillstand at the 800-foot level would ensure a low gradient for the Finn of the time, and a mouth far down the valley. In such conditions there is no obstacle to inferring that the discordant Finn rose as far west as the present confluence of the Stranagoppoge, competing with short streams draining to the west. Gubbin Hill and the shorter parallel hill between the Finn and the Cummirk are taken for remains of a marine bench, from which small stacks and islets protruded, while the shore of the 800-foot sea is provisionally traced along the north-west edge of the quartzite belt. If this interpretation is correct, the Finn has been able, since the recession of the 800-foot sea, to extend a tributary across the quartzite, through a col where dislocations converge (Fig. 5), and to invade the weak schists beyond. The Cummirk, crossing the quartzite in right-angled bends, seems wholly concordant in its uppermost parts. In both basins, the east-flowing rivers are thought to have disrupted or reversed former feeders of the Gweebarra.

(*ii*) *Country between Aghla Mountain and the Blue Stack Group.* In the triangle marked by Aghla Mountain, Silver Hill and Boultypatrick, the rivers Stranagoppoge, Glashagh, Stracashel, Owenea and Reelan are in competition (Fig. 4), the present divide running from Aghla Mountain on to a long, flat crest more than 700 feet high, turning through a right angle, and winding round the head of the Reelan into the granulitic hills west of Blue Stack. Charlesworth puts the ice-shed on this part of the divide, and nothing seen on the ground indicates glacial breaching, despite severe gouging in the valleys of the Stracashel and Owenea. The various benches in Fig. 6, mainly between 500 and 700 feet, seem to be little-modified remnants of pre-glacial valley-floors, into which rejuvenated subsequent streams had been somewhat incised before the onset of glaciation.

The belt of dislocation running north-east–south-west on the west of Boultypatrick, Silver Hill, and Carnaween (Fig. 5) is not yet fully studied; it is thought, however, to result principally from tear-faulting, and to extend right across Donegal. Without prejudice to the work of others, the dislocation will be referred to below as the Kilmacrenan–Killybegs line. In the locality under discussion both it and the landforms associated with it are complex in detail, as may be seen from the faults marked diagrammatically in Fig. 5, and from the relief-features partly indicated in Fig. 6. A narrow fault-bounded strip of quartzite (not the Slieve Tooey Quartzite) rises west of Silver Hill in a ridge which, on its south-east side, encloses a wide, boggy flat with lake-basins cut in the floor, but the dislocation is expressed mainly by a fault-line scarp descending abruptly to the north-west. West of the present head of the Reelan, erosion by ice and water has

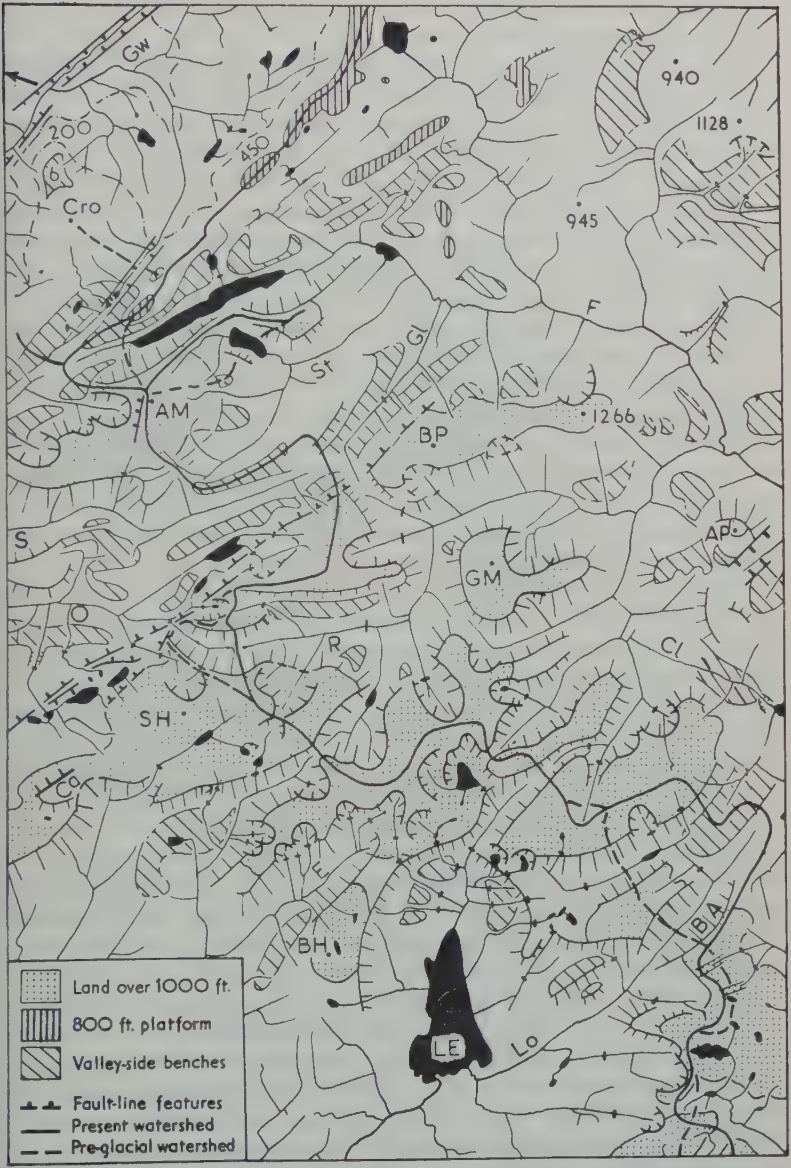

Fig. 6. Southern part of the main watershed: some morphological distributions. Erosional platforms at high levels are not distinguished

left slices of rock rising in thick walls, and has gashed the hillside which runs away to the north-east.

(*iii*) *High Ground from Silver Hill to Barnesmore*. It has previously been shown that the divide at the head of the Reelan has been shifted to the east by glacial breaching in two places, that low points on the crestal watershed of Blue Stack are located on faults, and that dykes in the Barnesmore area guide a number of minor streams (Dury, 1958; cf. Walker & Leedal, 1954, and Leedal & Walker, 1954). A few Tertiary dykes are marked by heavy dotted lines in Fig. 5. As in the Glendowan and Derryveagh Mountains these dykes are far more numerous and far more effective in guiding streams than the annexed maps suggest. Caledonian dykes in the Barnesmore Granite have little effect on landform except where they are close-set. Glacial breaches previously identified in the east of this area include that at the head of Barnes River west of Barnes Lough (BL, Fig. 4), that of Barnesmore (BA), and minor breaches in the crestal belt south of Barnesmore (Dury, 1958); an additional breach is now claimed for the high col north-west of Barnes Lough, west of the spot-height 1795 in Fig. 4, where the divide appears to have been displaced slightly to the south, and further minor breaching has probably occurred also on the glacially roughened plateau-top south of Barnesmore.

The only two marked breaches remain those of the Barnes Lough and Barnesmore trenches, through which ice moved to the north-east. The local divide at the head of the Barnes Lough trench was somewhat lowered, a col at 800–900 feet being ground down and its sill shifted towards the south-west, but post-glacial drainage, accommodating itself to the faults which converge on the head of the trough (Fig. 5), is still far from settled. The Barnes River below Barnes Lough is collected by the south-east-flowing Lowerymore, which anomalously crosses the line of the breached divide against the direction of ice-movement, being separated from the Mourne Beg by a bulky spread of coarse outwash.

A small gap in a minor watershed at the head of the Clogher (Fig. 8) represents a further glacial breach, which has not previously been described. The present head of the Clogher flows north-east for half a mile into Lough Sallagh, which discharges westwards through a tiny gorge. The north-east-flowing headstream is in line with the Rough Burn, a subsequent tributary of the Finn, and also with a subsequent feeder of the Mourne Beg which flows into Lough Mourne. The Clogher Valley closes firmly in below Lough Sallagh, suggesting that the local pre-glacial watershed should separate the site of Lough Sallagh from the Clogher; if so, the head of the Clogher above Lough Sallagh formerly belonged either to the Rough Burn or to the Mourne system. Even though basal ice is known to have moved north-east down the whole depression, which is constricted just beyond the lower end of Lough Sallagh, the long continuous slope from the present head of the

Clogher into the present valley of the Rough Burn suggests that pre-glacial drainage was to the latter, and the pre-glacial divide at the head of the Rough Burn may have lain where a shallow, boggy col occurs at about 700 feet. Similar competition between the Finn and Mourne Beg systems may be inferred, at a lower level, near the present site of Lough Mourne.

(*iv*) *Reelan System.* Corrie-cutting and gouging of troughs were severe north of the Blue Stack group, where much of the pre-glacial surface was destroyed. Nevertheless, prolonged and successful normal erosion is indicated by wide valleys on three sides of Gaugin Mountain, by valley-side benches at low levels, and by extensive mountain-shoulders at high levels. Although the geology is too little known for the extent of adjustment to structure to be assessed, it can be said that the uppermost three miles of the Reelan run parallel to the strike of a narrow strip of quartzite on the valley-side, that the reach west of Gaugin Mountain is parallel to a fault, and that streams south-east of Gaugin Mountain—including the Owengarve and the Owendoo—follow north-east courses along, or parallel to, known fault-lines. Among the noteworthy single features is the severely eroded south-east side of Altnapaste, where the Lough Belshade tear-fault has been cleanly excavated. The broad lower valleys of the Reelan system testify to the power of the pre-glacial Finn, which provided the local base-level.

3. GENERAL VIEW OF THE MAIN WATERSHED

When allowance is made for glacial breaches, the main pre-glacial watershed (with certain minor branches) can be reconstructed (Fig. 8). Serial numbers refer to Table I, where the effects of breaching are summarised.

Drainage-patterns in the South-west, South and South-east

In Fig. 1, which gives a somewhat greater cover of districts west and south of the main watershed than do Figs. 1–6, the generally discordant character of the (pre-glacial) Gweebarra appears with greater clarity than hitherto. There are signs of east–west elements in the courses of the Stracashel and Owenea, even though minor streams are aligned on the internal structures of the Ardara Pluton and on the curving strike of metasediments on the northern border (Iyengar, Pitcher & Read, 1954; cf. Akaad, 1957). In the present context, possible relics of east–west drainage in western districts are significant complements of west–east drainage on the other side of the watershed.

On the Carboniferous rocks of the Donegal syncline (cf. George & Oswald, 1957), some streams are aligned on south-west–north-east faults, and others are adjusted to the strike of the sedimentary strata; the presence of dip-streams is suspected, but needs further investigation. Superimposition from a wasting Carboniferous cover may have occurred locally, but no substantial remnants of the sub-Carboniferous floor have been identified round the margins of the Donegal syncline. The drainage-pattern is complicated by closely grouped and ice-eroded fault-lines east of Lough Eske, and by numerous fault-lines between Lough Derg and the edge of the Carboniferous outcrop in the Omagh syncline (Anderson, 1947; cf. Simpson, 1954). Strike-streams are well developed on the Claragh Sandstone in the neighbourhood of Bin Mountain, where similar streams may have been superimposed on the Dalradian undermass just north of the present limit of the Carboniferous, but the Derg, down to its confluence with the Mourne Beg, is roughly aligned on a fault, and if this fault—like faults transecting the Donegal syncline—was posthumously active in Carboniferous or later times, the Derg may have developed as a fault-guided subsequent on Carboniferous rocks and have been superimposed from them with very little modification.

4. EASTERLY DRAINAGE

(a) Dergan, Mourne Beg and Finn

The Dergan in much of Glendergan, and the Mourne Beg throughout its course, cut at high angles across the strike of Dalradian rocks and across south-west to north-east faults (Fig. 8). The Finn, partly discordant to structure west of the Kilmacrenan–Killybegs line, turns along the strike past Crocknahamid, but then resumes an easterly course for fifteen miles before turning north-east below Castlefinn towards the Foyle. It traverses the Lough Belshade tear-fault which, with a horizontal displacement of more than two miles, leaves half of a patch of quartzitic rock on one side of the river in Altnapaste, and the other half in Gorey Hill on the other side (cf. Leedal & Walker, 1954; Walker & Leedal, 1954). Subsequent tributaries of the Finn between Crocknahamid and Castlefinn are generally aligned on, or parallel to, north-east-trending faults.

(*i*) *Deele and Raphoe Swilly*. The general parallelism of much of the Finn, parts of the Deele system, the Letterkenny Swilly, and parts of the Bullaba, Sruhaneam and Leannan suggests very strongly that the present stream-net has evolved from an array of superimposed east-flowing consequents. Sequences of pre-glacial capture by which these consequents were partly dismembered are most readily constructed for the Deele.

The upper Deele west of Convoy is aligned on the Raphoe Swilly, while the Cloghroe is aligned on the lower Deele east of Convoy. The present valley around Convoy is so wide and deep that the upper Deele and the Raphoe Swilly can be connected by a restored stream which, following the east–west line of a feeder north-west of Convoy, does not cross the 300-foot contour. The upper Cloghroe occupies a wide, rather shallow head-valley, descending from the 500-foot level through a defile into the main valley; if it once flowed direct to the lower Deele, the wide valley around Convoy combines the former valleys of two separate streams, and thus represents the result of abstraction. The Deele system appears to have been favoured at the expense of the Raphoe Swilly by becoming adjusted to the strike of Dalradian metalimestone in the two-and-a-half-mile stretch from Convoy downstream (Fig. 8); lesser examples of similar adjustment can be observed on smaller streams. At the lower end of the adjusted reach, the Deele has shifted to the south of its postulated former west–east line, while at the upper end it has shifted to the north, invading the former territory of the Swilly and capturing the present upper Deele. The restored Cloghroe–Deele should be traced south of Convoy and across the adjusted reach towards Ballindrait.

The stream named as the head of the Deele empties from Lough Deele, a mile north-west of Cark Mountain (Fig. 8), but the Sruffannagallagh on the south-east side of Cark Mountain should be taken to represent the original line of the reconstructed upper Deele–Raphoe Swilly. Although the Sruffannagallagh enters the Deele from the south-west at a right angle, the form of the confluence has little probable bearing on the detail of pre-glacial topography, for the valley-bottom is thickly drift-strewn, and a great tongue of debris occupies the angle of the confluence. Much of this drift—and possibly all of it—may be outwash from meltwater which, running through the col at the head of the Elatagh, entered an ice-dammed lake in the Sruffannagallagh Valley, and found an outlet through a col into the valley of the Letterkenny Swilly.

The two spillways, and other spillways marked in Fig. 8, are among those identified by Charlesworth, who has traced the sequence of ice-damming which produced temporary lakes (Charlesworth, 1924). Heights of intake, where not recorded by Charlesworth, are inserted by reference to the contour map; the heights of a number of other cols, in the form about 850, are also taken from the map, being inserted for use in discussion of river-capture. In general, the various spillways discharged towards the north from lakes impounded by north-facing ice-fronts. Some of the spillway floors are flat and boggy, with ill-defined partings between competing streams, but there are few signs of deep erosion by spillwater or of appreciable displacements of the pre-glacial divide, with the result that spillways serve to fix the line of the former watershed at low points on the interfluves, and to indicate the depth of passes at the time of ice-retreat. Like the large consequent valleys, the passes indicate prolonged normal erosion in pre-glacial times.

The pre-glacial divide between the Deele and the Letterkenny Swilly, drawn through the spillways which intake at 370 and 570 feet north and north-west of Convoy, continues rather south of west through a group of hills and crosses a third spillway intaking at 660 feet. The uppermost

Deele north of Cark Mountain then becomes a pre-glacial tributary of the Sruffannagallagh—upper Deele—Swilly. Draining a very wide valley between Cark Mountain and Cronamuck (1134 feet), the uppermost Deele seems to represent an ancient element of the stream-net, but it is difficult finally to refer it either to the Raphoe Swilly or to the Letterkenny Swilly, for hills rising above 900 feet east of the present confluence with the Sruffannagallagh offer little scope for its extension eastwards. Because the form of its valley resembles the valley-forms of the middle Deele and the Cloghroe, it seems, however, to belong south rather than north of the pre-glacial watershed. If the uppermost Deele represents a whole consequent, then all but a small reach of the original stream has long vanished.

(*ii*) *Streams in the area Cark Mountain–Crocknahamid–Binswilly.* Just as the Raphoe Swilly has been deprived by the Deele, so the Deele has lost territory to the Letterkenny Swilly and to the Finn, feeders of which, competing between Cark Mountain and Binswilly, enclose the basin of the Deele. The head-valley of the uppermost Deele ends in a col about 850 feet high, with no trace of headward extension on the broad southern slopes of the Swilly Valley, but an earlier line of a longer Sruffannagallagh may be represented by the westward-flowing Elatagh; if so, the upper half of the present Elatagh is a reversed consequent. Still farther west, part of the locally discordant Cummirk might represent part of the same dismembered consequent, despite the difficulties occasioned by the 800-foot platform (see above), and the discordant reach of the Finn north-west of Crocknahamid may similarly indicate the former line of a longer Cloghroe–Deele which crossed the site of the col (about 900 feet) at the head of the present Cloghroe.

Two miles south of Binswilly occurs a trench, half a mile wide at the bottom, floored with bog, and well over 100 feet deep (Fig. 6, and spot-height about 650 in Fig. 1), quite unlike most of the cols which cross the west–east divides. It might belong to those early valley-systems which are recorded in the broad lateral slopes and benches of the Finn, being encroached on pre-glacially, as today, by the head of the Letterkenny Swilly, but no interpretation which has so far come to mind seems really adequate. As for the Letterkenny Swilly itself, nothing on the ground suggests that its consequent course should be extended on to the Main Donegal Granite. Some of the probably dyke-guided or joint-guided subsequents on the granite might, however, represent adjusted feeders of the Swilly, comparable to the former adjusted heads of the pre-glacial Bullaba.

(*iii*) *Eastward Drainage North of the Letterkenny Swilly.* If, on the evidence previously noted, an old course of the Bullaba is to be projected along the Sruhaneam, it may be inferred that the Bullaba–Sruhaneam was dismembered by a subsequent tributary of the Leannan. This tributary, working headward along the line marked by Gartan Lough, seems to have intercepted the Bullaba–Sruhaneam at a height of something over 400 feet (cf. spot-heights in Fig. 8), but one or more additional captures must be postulated farther east. The present Sruhaneam is directly aligned on a high col (about 850 feet in Fig. 8) between Gregory Hill to the south and Croaghmore (over 1000 feet) to the north. These two summits are the culminations of a hill-mass some three miles across and 600 or 700 feet higher than the surrounding country, so that, if the feeder of the Sruhaneam which now drains westwards from the 850-foot col is a reversed consequent comparable to the Elatagh, reversal must have occurred long ago. The lower Sruhaneam, a subsequent of the Leannan guided by the Kilmacrenan–Killybegs dislocation, may have encountered the Bullaba–Sruhaneam at about 900 feet, at a time prior to the interception at 400 feet-plus south of Gartan Lough. Quite recent severe competition between the Letterkenny Swilly and the Leannan systems is indicated by the col at about 225 feet west of the Gregory Hill–Croaghmore mass.

Some semblance of a west to east line can be traced in the drainage from Lough Inshagh, into and out of Gartan Lough, and down the Leannan as far as the Kilmacrenan–Killybegs line, where the Leannan turns into a subsequent course to Lough Fern. How much the disturbance of west to east drainage owes to glaciation is difficult to judge, especially since drumlins occur in the Leannan Valley, around Lough Fern, and in the broad low pass at about 190 feet between the Leannan and the Glashagh, but although the depth of drift in this pass is unknown, it is possible that a Leannan–Glashagh may have been captured by the subsequent lower Leannan, on the Kilmacrenan–Killybegs line and at a height of less than 200 feet. As with the Sruhaneam, it is impossible to suggest a direct course farther to the east except at much higher levels—in this case, through a col at about 650 feet in the hills three and a half miles north-east of Letterkenny.

The Calabber has already been identified as discordant to the Main Donegal Granite. Any extension farther to the east must be made to pass through the broad, flat-floored col at about 450 feet which separates the present Calabber system from the Lurgy. The objections to such an extension are less powerful than might appear, even though the broad hill-girt depression near the lower end of Lough Veagh leads north-west along the Owencarrow to Glen Lough by a wide gate some 100 feet above sea-level. Not only does the col at about 450 feet connect the two valley-systems—the course of the Lurgy is much disturbed by drumlins, and no relief-features on the solid prohibit the restoration of a valley running more or less directly east to Rathmelton. If a Calabber–Lurgy ever existed, it has been dismembered by two feeders of the Owencarrow which developed along lines of structural weakness in the granite, the easterly breaking across the consequent course at a height of 450 to 500 feet and the westerly at an unknown but possible similar level.

5. IMPLICATIONS OF RECONSTRUCTED CONSEQUENT DRAINAGE

The preceding suggestions are brought together in Fig. 7, which shows the pattern of reconstructed consequents east of the main watershed, and selected consequents west of that line. To some extent it is possible to follow Charlesworth (1953, 190) in distinguishing a kind of radial pattern, for the southerly component in stream-direction increases progressively from the reconstructed Deele and Raphoe Swilly, through the Finn, to the Mourne Beg and the Dergan. On the other hand, the upper half of the Letterkenny Swilly, the Bullaba–Sruhaneam, the Lough Inshagh–Leannan, and the Calabber–Lurgy all flow south of east rather than north of east, the apparent northerly component being due to modification of their partly subsequent lower courses.

Charlesworth (1953) regards the drainage of Donegal as probably inherited from an up-domed Cretaceous cover. Superimposition has undoubtedly occurred, but the nature of the cover can only be guessed; the two obvious possibilities are that the cover consisted of Chalk, and that it consisted of basalt. None of the generalised maps of past geographies (e.g. Jukes-Browne, 1911; Wills, 1951; Charlesworth, 1953) can fairly be expected to provide much help. Wills, indeed, hints broadly at repeated marginal sedimentation, with the Donegal area tending persistently to rise,

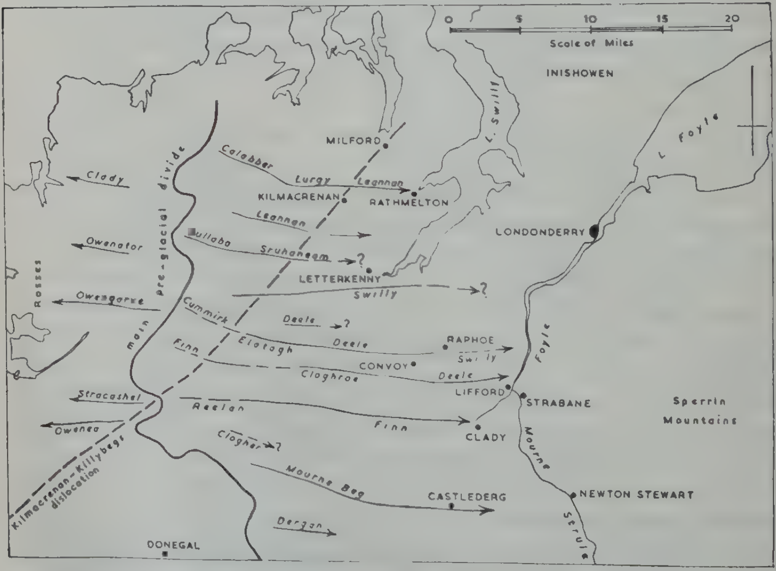

Fig. 7. Reconstructed west–east consequents, with some east–west consequents also shown beyond the main pre-glacial divide

and marginal conditions in Carboniferous times are confirmed by Simpson (1954), by George & Oswald (1957), and by Gill (1957) who, in drawing tentative isopachytes for the Carboniferous of north-west Ireland, outlines long offset basins striking east of north-east. Widespread superimposition from a Carboniferous cover can probably be ruled out, especially since the projected base of the Carboniferous passes well above summits in west Donegal (George & Oswald, 1957).

Because the Cretaceous Sea was notably transgressive, it may be suspected of once having submerged Donegal, but, even if it merely covered the edges of a repeatedly upwarped block, consequents on the flanks of the rising mass might easily have been extended seaward over a thin skin of emerging inshore sediments. In the absence of direct evidence of deep submergence, the superimposed streams of Donegal do not demand a broad westerly extension of thick Cretaceous rocks. On the other hand, Dr. J. M. Hancock informs me that the impression of a Chalk Sea extending little beyond the present Chalk outcrop may be erroneous. Although the Chalk of north-east Ireland thins away beneath the basalts and vanishes altogether near the Sperrins, part at least of the thinning is due to erosion in the period between the emergence of the Chalk and the extrusion of the lavas. Hartley (1938) tentatively infers that the Sperrins were up-domed during Tertiary times, complementary depressions forming—or deepening—on either side. Well over 400 feet of Chalk, and possibly more than 500 feet, are preserved in the Lough Neagh basin at the Washing Bay site, while well over 300 feet underlie Portrush (Hartley, 1948). If the depression west of the Sperrins was at all comparable with that on the east, Chalk may well have been preserved in it.

Wright's structural interpretation of north-east Ireland (Wright, 1919) is strongly supported by the results of gravity-survey (Cook & Murphy, 1952), even though gravity-anomalies suggest that the fills of hollows in the Palaeozoic floor differ from the fills inferred by Wright. Wright's postulate of a Lough Foyle syncline is also provisionally supported by the scanty geophysical data so far collected. Thus, although the height and attitude of Dalradian rocks in the Foyle Valley exclude a depression as great as the Lough Neagh depression, subsidence in the Foyle Valley is by no means ruled out.

It becomes necessary, therefore, to elaborate the hypotheses of superimposition as follows:

(a) That consequent streams rising in Donegal, and flowing eastwards at least as far as the Lough Neagh–Bann Valley line, were superimposed from a tilted unconformable cover of Chalk.

(b) That similar consequent streams were superimposed from a sloping surface of basalt, the Chalk wedging-out beneath the basalt east of the Strule–Mourne–Foyle line.

(c) That, although the Chalk wedged out as in (b), basalts were depressed by subsidence in the Foyle Valley.

(d) That, although the basalts reached well into Donegal, Chalk was downbent and preserved beneath them in the Foyle Valley.

(e) That the basalts extended little farther than their present limits, but that (i) Chalk was depressed and preserved in the Foyle Valley, or (ii) the Chalk had already been stripped off, and a subdued land-surface was sufficiently depressed to produce a new drainage-system tributary to an axial Strule–Mourne–Foyle.

Each of these hypotheses has its drawbacks, even though faulting be called to aid in depression. The great disadvantage of (a) and (b) is that they require the development of a large subsequent stream in the Foyle basin, without suggesting any reason for its origin and extension—unless, indeed, some weak outcrop or weak structure can be identified. Both hypotheses imply that west-flowing feeders of the Foyle, in Londonderry and Tyrone, are reversed consequents; but in that case, surviving portions of west–east streams in the west should be precisely aligned on reversed streams in the east, and it becomes difficult to avoid taking the Finn or some other large stream through the Sperrins by the Glenelly Valley. Hartley's map, however (1938), suggests that much of the Glenelly is subsequent, while west-flowing discordant streams occur, e.g. in the basin of the upper Roe. Thus a general projection of the Donegal consequents across the Strule–Mourne–Foyle line raises grave objections.

Hypotheses (c), (d) and (e) invoke Tertiary subsidence, for which no direct evidence can be offered; (e)(ii) demands the initiation of close-set parallel consequents on a deformed land-surface—a state of affairs difficult to imagine—while (d) requires similar consequents to arise on a surface of basalt. Whatever the difficulties, however, field observation does justify the conclusion that superimposition of west to east streams has taken place, and the east to west consequents provisionally identified west of the main watershed suggest that Tertiary upwarping affected Central Donegal. The main axis of upwarping seems to have run north to south in the north, but it is possible that doming took place in the Barnesmore–Blue Stack–Silver Hill district, in association with the emplacement of Tertiary dykes (cf. and cp. Walker & Leedal, 1954).

There is no *a priori* reason to think that Tertiary deformation of Donegal was any less complex or localised than the Tertiary movements which affected north-east Ireland, or than the contemporary depression of the floor of the Carboniferous Sea. For instance, it is proposed on a future occasion to show that the Glengesh Plateau in west Donegal has undergone a general tilt to the south. Meanwhile, and pending more geophysical work, the possibility of upheaval in the existing belt of high ground, and of depression in the Foyle Valley, seems worthy of serious consideration.

TABLE I. **Glacial Breaches Serially Numbered in Fig. 8**

Serial Number	Location	Estimated Lowering, feet	Estimated Horizontal Displacement
1	Muckish Gap[1]	200	½ mile
2	Lough Aluirg[1]	50–100?	½ mile
3	Altan Lough[1]	at least 400, possibly 500	2½ miles
4	Col between Errigal and Mackoght[1]	slight	slight
5	Col on NW. side of Errigal[2]	probably slight	small, towards the south
6	Col SW. of Slieve Snaght, on NE. side of Crockfadda[2]	probably slight	small; present divide ill-marked
7	Head of the Gweebarra	400–450	1 mile
8	Head of Glenveagh	500	2 miles
9	Owenwee Valley, SE. of Glendowan Mts.[3]	slight	1 mile
10	Gweebarra Valley[2]	200?	great; pre-glacial divide largely destroyed
11	NE. of Lough Finn[4]	50–100?	2 miles
12	Head of Lough Finn	200	1 mile
13	Col on SE. side of Lough Finn	100–150?	½ mile
14	Between Croaghubbrid and Croaghugagh[5]	50?	¼ mile
15	Head of the Reelan, near Bin More[5]	200	1 mile
16	2½ miles E. of Lough Belshade	probably slight	¼ mile (?) towards the S.
17	Barnes Lough[5]	300 or more	1¼ mile
18	Barnesmore[5, 6]	800?	2¼ miles
19	SE. of Barnesmore[5]	probably slight	probably slight
20	SE. of Barnesmore[5]	probably slight	probably slight
21	SE. of Barnesmore[2]	probably slight	probably slight
22	Near the head of the Clogher	probably slight	½ mile

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[1] Described in Dury (1957).

[2] Not previously reported, but not described in detail.

[3] A second similar breach is thought to occur in the adjacent Owenbeg Valley: see text.

[4] Horizontal displacement due to diversion of Glenleheen Stream into fault-line trench.

[5] Described in Dury (1958).

[6] Horizontal displacement due to diversion by outwash: see text.

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I take great pleasure in recording the generous assistance which I have received in my work on Donegal. To D. G. A. Whitten and G. T. Raine I am ultimately indebted for my introduction to the area. N. Stephens very generously communicated, and discussed, his manuscript study of the

drainage of north-east Ireland. A. Farrington has been consistently encouraging, and has most helpfully edited my two papers on glacial morphology which have appeared in *Irish Geography*. R. W. D. Elwell most kindly advised me on the structure (still under study) of the district around Silver Hill, and J. M. Hancock has, with equal kindness, discussed the implications of his work on the western margins of the Chalk. At all stages, W. S. Pitcher has been liberal both with time and with information; I am especially grateful to him for the use of a detailed map of the Main Donegal Granite and its envelope, and for advice on the connections between subsequent streams and underlying structures. Irish friends have, by their liberal hospitality, enabled me to carry out field-work which would otherwise have been impossible.

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A New Inarticulate Brachiopod from the Dorset Corallian

by D. V. AGER

Received 17 June 1958

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2. *DISCINISCA SANDSFOOTENSIS* sp. nov. 29
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ABSTRACT: A new inarticulate brachiopod—*Discinisca sandsfootensis*—is described from the Corallian (Upper Oxfordian) of the Dorset coast.

1. INTRODUCTION

APART FROM *Thurmannella thurmanni* (Voltz), which is common in certain beds in Yorkshire, brachiopods are extremely rare and local in the British Corallian. No members of the Inarticulata appear to have been described previously either from this formation or from the rest of the Oxfordian.

The single specimen here described was found by Mr. W. Bakiewicz on a student excursion from Chelsea College of Science and Technology to Weymouth. The finder kindly presented the specimen to the author, who has now passed it on to the British Museum (Natural History).

The regrettable rarity of brachiopods in the Corallian may be attributed to the unusual facies of that formation. Arkell once commented (1933, 562) with reference to the Jurassic that ‘ammonites . . . are always rare in coralline provinces’. Similarly it might be said that brachiopods and reef corals are also unusual bedfellows. This remains true to the present day, for only one brachiopod, *Frenulina*, is known to live on modern coral reefs. Many other associations and non-associations spring to mind in this connection. Thus brachiopods rarely seem to occur in the Jurassic closely associated with specimens of *Trigonia*, except perhaps for highly specialised types such as *Acanthothiris spinosa* in the Upper *Trigonia* Grit. Species of *Trigonia* are of course particularly abundant in the Corallian on the Dorset coast.

Muir-Wood has observed (1928, 469) that ‘all Recent Disciniscas are tropical, marine and shallow-water forms occurring as a rule at depths of up to twenty fathoms. . . .’. Comparable forms to that described here are found today ‘at a depth of five to nine fathoms off the coasts of Chile and Peru and western shore of North America. . . .’. This may be of significance in connection with discussions of the climate prevailing in Corallian times.

2. *DISCINISCA SANDSFOOTENSIS* sp. nov.

Plate 1, figs. A, B.

1877. *Discina humphresiana* (J. de C. Sowerby); Blake & Hudleston, p. 271.

Diagnosis. *Discinisca*, about 55 mm. long, 40 mm. wide and 40 mm. thick. Both valves conical and elliptical in outline. Shell thin, chitinous. No radial striae, growth lines numerous on both valves.

Holotype. B.M.N.H. No. BB. 20460 from the Sandsfoot Grit of the Corallian (Upper Oxfordian), in the cliff section below Sandsfoot Castle near Weymouth, Dorset. This is the only specimen known.

Description. Upper (dorsal) valve: The distance of the apex from the posterior margin is about one-third of the length of the valve. It is about 25 mm. thick and has about eight regularly spaced growth-ridges, with finer growth-lines in between. There are about thirty concentric markings altogether produced by slight variations in the rate of growth. There is no trace of any radial ornament. The shell is thin, chitinous and dark brown in colour.

Lower (ventral) valve: This is exactly like the dorsal valve except that it is smaller (about 16 mm. thick) and its apex is nearer the anterior end of the shell. There are again about thirty concentric growth-markings, which supports the idea that this is the ventral valve of the same specimen, and not a second dorsal valve. The posterior part of the valve is not preserved, so nothing is known of the pedicle opening.

3. DISCUSSION

'*Discina*' *humphresiana* was recorded from the 'Sandsfoot Castle Beds' by Blake & Hudleston (1877, 271). This name applies to a form which is otherwise only known from Kimeridgian and Portlandian. As originally figured by J. de C. Sowerby (1826, pl. 506, fig. 2) and as later figured by Davidson (1852, p. 10, pl. I, fig. 3, and 1876, p. 81, pl. XIII, figs. 17–19), this is specifically identified by its radial striae. These are absent on the specimen described here. What is more, Sowerby's species is apparently much smaller and has a concave ventral valve.

Dall (1920) recognised three groups of living Disciniscas:

(i) Large thin-shelled forms with no radial ornament.
(ii) Large thick-shelled forms with faint radial striae and concentric lamellae.
(iii) Small thick-shelled forms with a regular radiating ornament

D. sandsfootensis would belong to the first of these categories. Only two species without radial striae were recorded from the English Jurassic by

Muir-Wood (op. cit. 468). These were *D. holdeni* (Tate) from the Lias and *D. reflexa* (J. Sowerby) from the Lias and Inferior Oolite, both of which are much smaller than this species and lack the distinctive conical ventral valve.

A few other rare specimens have been imperfectly described from various formations, e.g. *D.* (?) *annulosa* (Davidson), but they are all very much smaller in size. The only Mesozoic form which is at all comparable in size and form is *D. babeana* (d'Orbigny) [= *D. townshendi* (Davidson)] which has the distinction of being the only brachiopod known in the British Rhaetic (Upper Triassic). It can be distinguished, however, by the extreme anterior position of the dorsal apex and the concavity of the ventral valve.

The form which most closely resembles the one here described is *D. lamellosa* Broderip which lives at the present day off the western coast of North and South America. This has both the strong concentric ornament and the anteriorly conical ventral valve. It differs in its somewhat smaller size and in the flattening of the ventral valve posteriorly.

EXPLANATION OF PLATE

Discinisca sandsfootensis sp. nov.

Holotype. Sandsfoot Grit, Corallian (Upper Oxfordian), Sandsfoot Castle, near Weymouth, Dorset. A: lateral view showing the dorsal valve above and the ventral valve below; B: dorsal view. The specimen B.M.(N.H.)B.B. 20460 was coated with ammonium chloride before photographing.

Magnification × 2 approximately. The photographs were taken by Miss Elaine Bryant.

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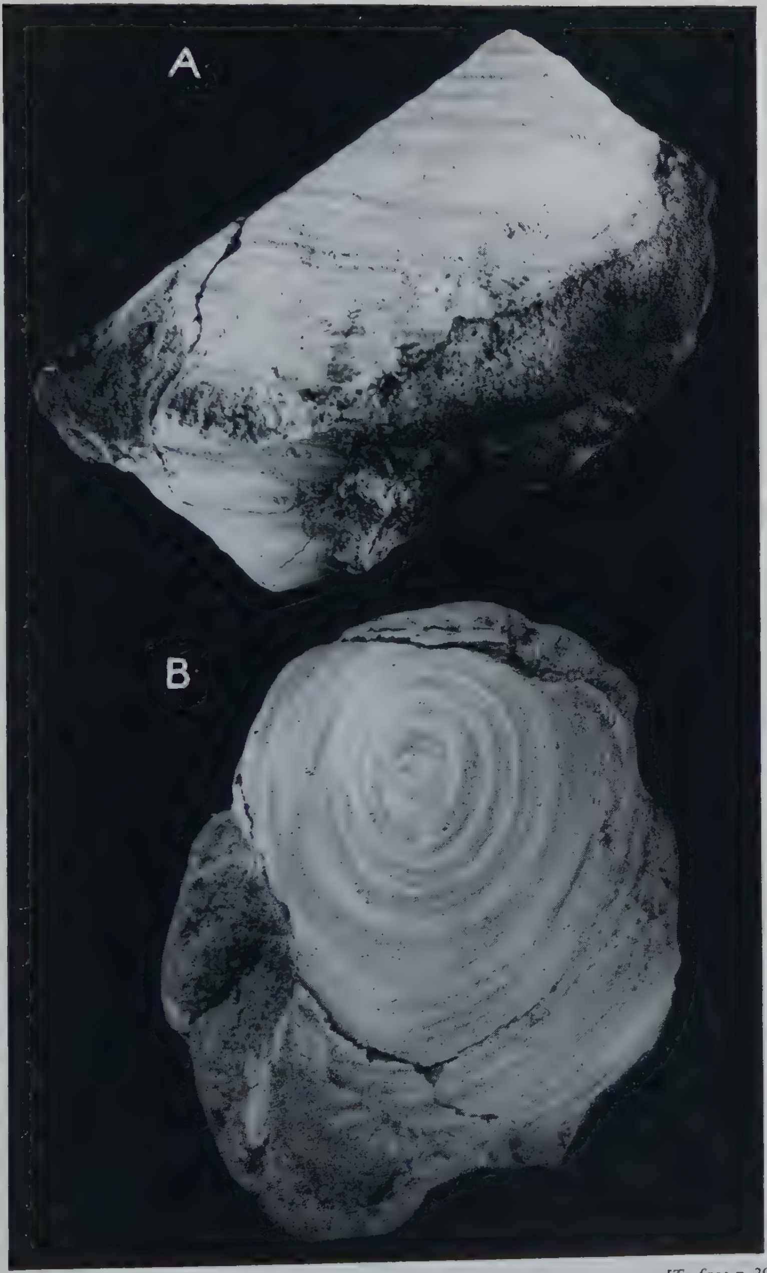

[*To face p.* 30

Field Meeting at Selborne, Hampshire

THE GEOLOGY OF GILBERT WHITE'S COUNTRY

4 October 1958

Report by the Director: F. A. MIDDLEMISS

THIS MEETING was designed to show the strata best known to Gilbert White and described by him in *The Natural History of Selborne*, and to demonstrate the accuracy of his geological observations in that work. Forty-seven members attended and were transported in one forty-one-seater coach, with three private cars following. Each member was supplied with a geological itinerary of the outward journey from London, which was by way of the main Portsmouth road as far as Liphook.

The Field Meeting proper began at Weaver's Down (813307),[1] in Woolmer Forest, the summit of which provided a good view over the country to be visited during the day. Here also coarse, pebbly sands of the Folkestone Beds, some 160 feet above the base, are well exposed.

The next exposure visited was at the Honey Lane Brickworks, about one and a half mile east of Selborne (768342) (Selborne Brick & Tile Company Ltd.). In the extensive pit here are several exposures of slightly silty Gault with much dispersed gypsum and a little pyrites. The clay is almost massive when fresh but shows a poorly developed bedding when weathered. In the western face of the pit there is a twelve-inch-thick seam of red clay-ironstone. The fauna is chiefly of ammonites preserved as casts and found in both the ironstone and the clay. The commonest forms are Hoplitids (identified by J. M. Hancock)—*Hoplites dentatus* (J. Sowerby) and varieties, *H*. aff. *spathi* Breistroffer and *H. latesulcatus* Spath, indicating the *dentatus-spathi* Subzone of the *dentatus* Zone. Also found were *Hamites* sp., *Nucula* cf. *pectinata* J. Sowerby, *Inoceramus concentricus* Parkinson and *Cardiaster* sp. These are apparently the first records of fossils from this exposure which had yielded none when the pit was recorded by Osborne White (1910).

After lunch at the 'Red Lion', Oakhanger (769359), the party set out to make a traverse on foot to the Upper Greensand plateau. In the lane immediately north-west of the inn a small pit in the top part of the Folkestone Beds was examined; small-scale current bedding from a north-westerly direction is well developed, while the true dip can be seen to be about 2° west-north-west. The Gault is not exposed along the lane towards Hartley Mauditt but typical damp meadowland, in Gilbert White's time forested with oaks, was seen. The topography around Candovers Farm

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[1] Grid references refer to 100 km. square, 41 (SU).

(756358) shows that extensive landslipping has occurred where the Upper Greensand overlies the Gault, the back of the slipped mass being the steep escarpment of Upper Greensand running through Park Hanger. Just here, at the top of the hill (751360), the lane is sunken and affords one of the best local exposures of the massively bedded malmstone of the Upper Greensand, dipping at 2° to the west. Large specimens of *Mortoniceras* sp. can sometimes be found here. In this cutting the party was given an unwelcome demonstration of the process of formation of sunken lanes by a colossal downpour of rain, through which the members hurried across the level surface of the Upper Greensand bench to Hartley Park Farm. Here, after vigorous wringing out of clothing, the coach was rejoined and the journey to Selborne village was completed.

A visit followed to Gilbert White's house, The Wakes, which is now administered as a museum (Resident Curator Mr. C. R. Nortcliffe), and tea was enjoyed at the Queen's Hotel, during which a vote of thanks was proposed by Dr. J. M. Hancock.

The meeting ended, as it had begun, with a view, clear weather having followed the rain. The viewpoint was the eastern end of Selborne Hanger (741332), at the top of the zig-zag path, which affords a very fine view over the western end of the Weald. In particular the characteristically rounded forms of the Chalk of Selborne Hill and Noar Hill, with at their feet the extensive bench of Upper Greensand bearing orchards and hop-fields, were pointed out, while to the south-east the dip slopes of Lower Greensand surrounding the westerly plunging anticlines of the Vale of Fernhurst could be seen, and beyond them the 'vast range of mountains' of the South Downs, as Gilbert White called them.

On the return journey a brief halt was made near Empshott (762311) for a distant view of the scar of the great Hawkley landslip of 1774 (Gilbert White's Barrington Letter No. 45).

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[1] A list of White's references to geology is given by Sclater & Whitaker, 1892.

The Superficial Deposits of the Buried Valley of the River Devon near Alva, Clackmannan, Scotland

by A. PARTHASARATHY and F. G. H. BLYTH

Received 7 February 1958; taken as read 3 April 1959

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ABSTRACT: The buried valley of the River Devon, known from a small number of deep borings to underlie the present alluvial tract, was explored by means of a resistivity survey. Samples of the carse deposits, late-Glacial clays and boulder-clays in the area of the buried valley were obtained by augering and from a new borehole near Alva.

The physical characters of the clays were determined by the methods of soil mechanics. Their mineral composition was estimated by differential thermal analysis and X-ray studies. The results suggest an estuarine origin for the late-Glacial clays (correlated with the '100 foot' Raised Beach deposits), the estuary being characterised by fjord-like over-deepening in the neighbourhood of Alva.

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1. INTRODUCTION

THE RIVER DEVON in Clackmannanshire flows westwards past Dollar, Tillicoultry and Alva over a flat alluvial plain (the carse) at the foot of the Ochil Hills, to join the Forth some three miles east of Stirling (Fig. 1). A buried valley, the old pre-Glacial course of the Devon, lies below the carse in the neighbourhood of Alva and Tillicoultry, and was excavated in the Coal Measures. It is now filled with deposits of late-Glacial and post-Glacial age, and its depth at a number of points is known from borehole data obtained in the Clackmannanshire coalfield. The maximum depth recorded is 351 feet, in a boring two-thirds of a mile south-east of Alva, near Kersiepow. Two other boreholes in the area proved 'rockhead' at depths of over 300 feet.

The course of the buried channel, which was largely conjectural in the past, lies slightly to the north of the present river near Alva, and is known to continue as far west as Menstrie. A discussion of the (then) known data relating to the channel was given by Cadell (1913), and further reference to it was made in the Stirling Memoir (Dinham & Haldane, 1932). Since the work described in the present paper was carried out, in 1953–4, a new description of the Stirling and Clackmannan Coalfield area north of the Forth has been published (Francis, 1956), in which a cross-section of the buried channel east of Tillicoultry is given. Its depth in this section is shown as somewhat less than 250 feet, confirming the earlier evidence for the deepening of the channel from east to west.

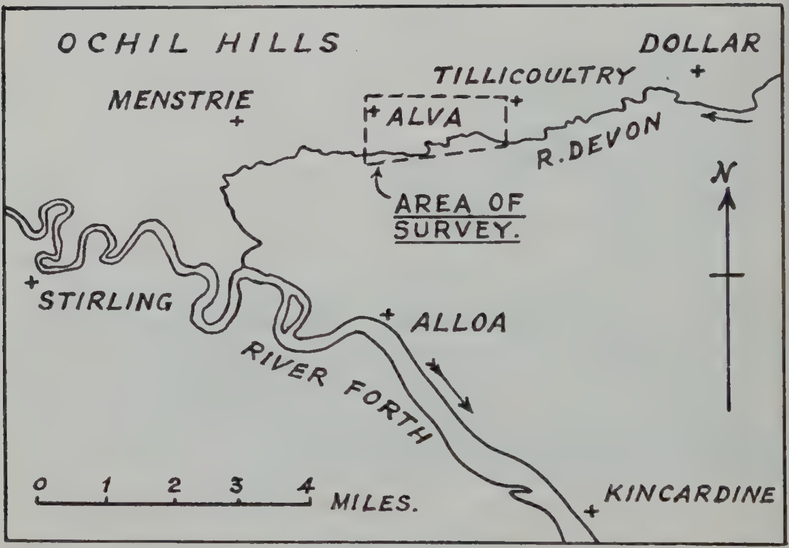

Fig. 1. Locality map

2. GEOPHYSICAL SURVEY

A resistivity survey, in which the first-named author assisted, was made near Alva and Tillicoultry, in order to trace the buried valley in greater detail and to estimate the thickness of the superficial deposits within it. This survey has been described by Vincenz (1954), and his map of the equi-resistivity contours obtained is reproduced here in Fig. 2, with the alteration that the contours show estimated depths in feet below the surface instead of particular values of resistivity. The buried valley is inferred to be wide, with a somewhat steeper southern, as compared with the northern, slope. Borehole data were used to correlate the equi-resistivity contours

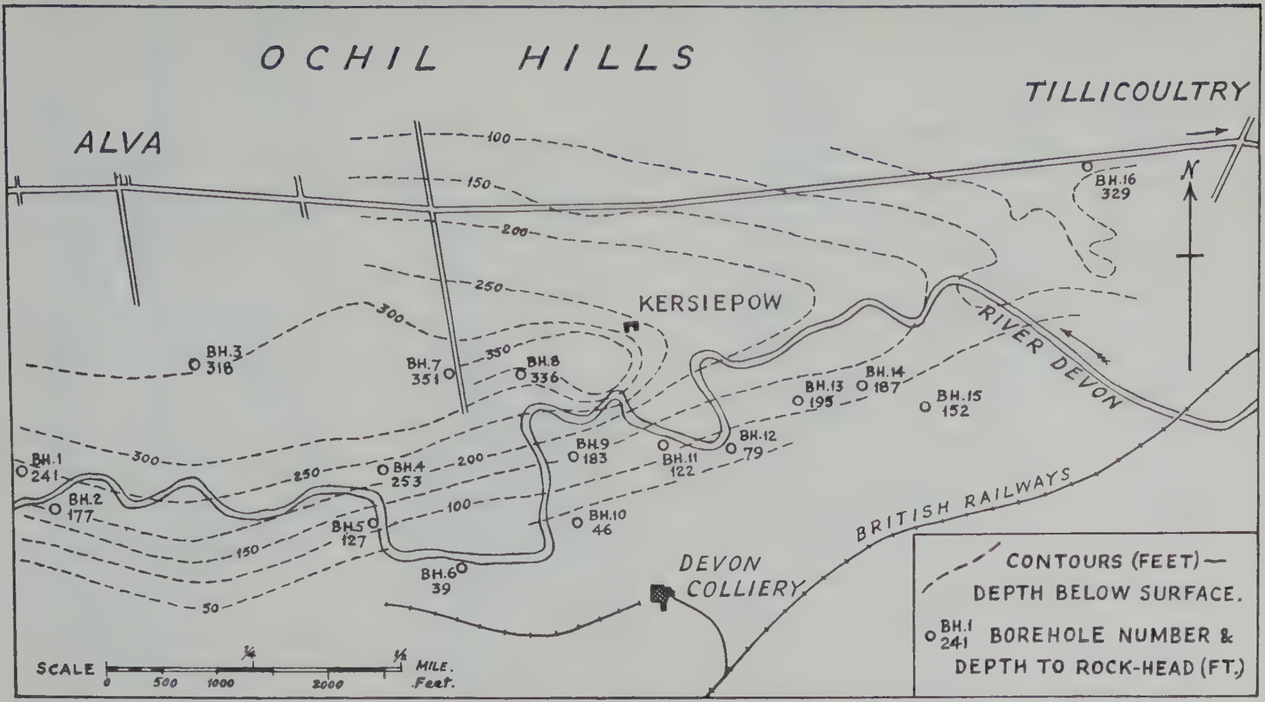

Fig. 2. Map of buried valley of the River Devon, near Alva, with sub-surface contours based on resistivity survey, after Vincenz

with depth below the surface. The very low resistivity area near Kersiepow suggests the presence of a 'hollow', where depths to the valley floor reach a magnitude of some 350 feet. Sedimentary layers within twenty feet of the surface had a higher average resistivity (2.7 to 20×10^3 ohm. cm.) compared to deposits at greater depths, where the values were much lower (0.3 to 7.5×10^3 ohm. cm.). The low values suggest that saline water is present in the deeper deposits.

Uniform conditions within the different layers of sediment (each of differing resistivity) are required for the method to reveal subsurface features such as a buried valley: such conditions seem to be present in the area west of Kersiepow, but to a smaller extent in the east towards Tillicoultry, where indications of the valley are less definite. The section (Fig. 4) is drawn from the contour data shown in Fig. 2.

3. THE SUPERFICIAL DEPOSITS

Deposits of the Devon Valley area include boulder-clays, sands, gravels and estuarine clays. Their surface distribution is shown in Fig. 3. A vertical section, compiled from three deep borings made near the Devon Colliery in 1929, was given by Flett as follows:

	Thickness (in feet)	
Soil	1	
Yellow clay	5¾	Carse clays[1]
Soft dark sandy clay	7	
Sands and gravels (? fluvio-glacial)	5	
Clayey sand with layers of clay	21	
Dark grey 'gutta percha' laminated clays	64	
Reddish and brownish 'gutta percha' laminated clays	120	
Brown clay with layers of sand	18	
Clean reddish sand, stones at base	12 to 42	
Reddish sandy boulder-clay with boulders of porphyrite, felsite, quartzite, Old Red Sandstone and Carboniferous limestone	7 to 51	

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[1] Clays of the '50 foot' Raised Beach, corresponding to the '25 foot' Raised Beach of the Lower Forth.

Boulder-clay was encountered in all the borings that reached the bottom of the buried channel. The group of deposits lying between the boulder-clay and the carse clays is undoubtedly connected with stages in the retreat of the great ice-sheet, and the thick, laminated, 'gutta percha' clays were probably accumulated in a late-Glacial sea (sea of the '100 foot' Raised Beach) (Flett, 1930, *loc. cit.*).

The above section illustrates the range of superficial deposits present in the area, and the general succession may be summarised thus:

5. Recent alluvium
4. Carse clays (≡ '25 foot' Raised Beach deposits)
3. Sands and gravels (early post-Glacial)
2. Late-Glacial marine clays (≡ '100 foot' Raised Beach deposits)
1, Boulder-clays.

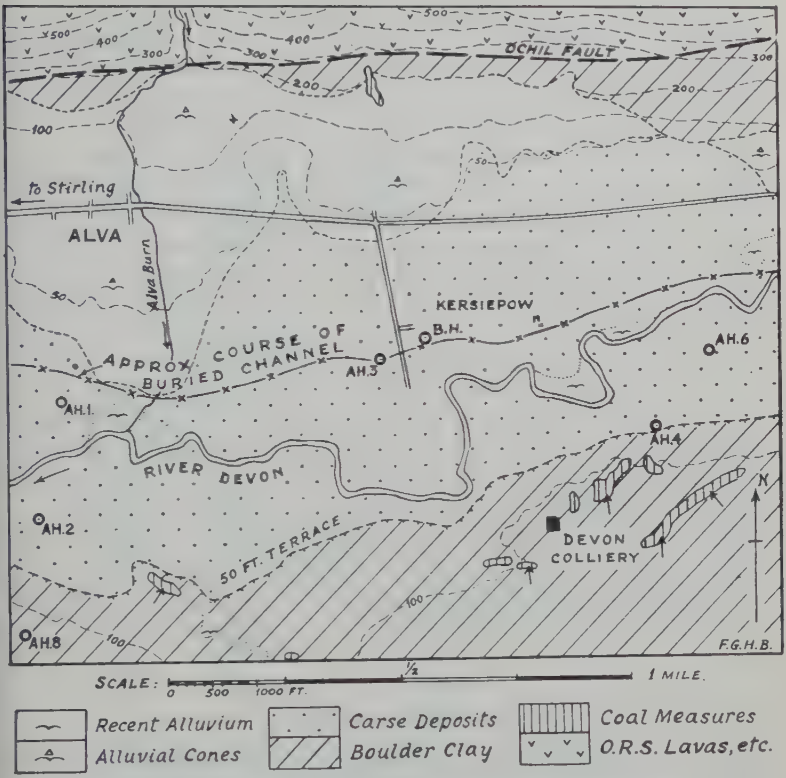

Fig. 3. Geological map of the Alva area. B.H. = new borehole at Kersiepow. A.H.1, 2, etc. = auger holes

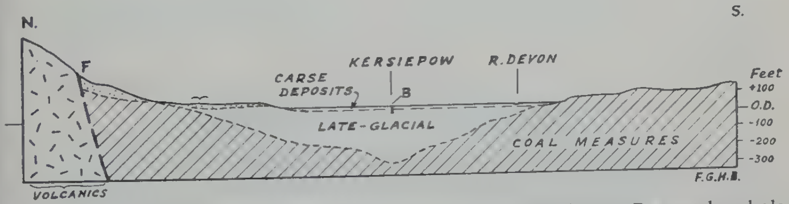

Fig. 4. Section from north to south along a line through Kersiepow. B = new borehole penetrating the carse deposits and upper part of the late-Glacial deposits of the buried valley, F = Ochil fault

After the formation of the boulder-clays, with the beginning of the retreat of the Pleistocene ice, the Forth area (including the Devon Valley) became covered by the sea, the level of which stood 100 feet or more higher than at present. The extent of this sea is marked by the so-called '100 foot' Raised Beach, and its deposits in the Forth area include coarser sands and gravels of the old coast-line, and also finer clays and silts (Lacaille, 1948).

The late-Glacial clays are laminated and generally free from large particles. They contain arctic shells, and were formed in cold, tranquil waters. The mineralogical content of the clays is discussed later (p. 46). With the melting of the ice the land rose slowly and a period of milder climatic conditions followed, marked by a bed of peat. Sands and gravels are found in association with, or in place of, this peat; they underlie the later-formed carse clays.

After the episode of peat formation the sea again encroached upon the land in the Forth area, and its coast-line stood at twenty-five to thirty feet above the present level. This post-Glacial marine transgression was responsible for the formation of the '25 foot' Raised Beach or platform (the height varies up to about fifty feet in the upper Forth Valley and elsewhere), and the Carse clays were deposited. The clays are dark blue to greyish in colour, and contain marine shells; they are considered to be identical with sediments now forming along the shores of the present estuary (Dinham, 1927). Warm and moist climatic conditions may have prevailed at the time of their deposition.

4. AUGER SAMPLES

Samples of the carse clays in the area studied were obtained by means of a six-inch hand auger, which reached depths up to about sixteen feet. Eight auger holes were made, of which six positions are shown in Fig. 3, marked AH. Boulder-clays near the surface were also sampled by augering. The data obtained in this way are given in Table I below.

None of the auger holes penetrated to the late-Glacial deposits below the carse clays, the latter being present up to depths greater than the range of the auger.

5. NEW BOREHOLE AT KERSIEPOW

A new borehole was therefore made to obtain samples of the late-Glacial ('100 foot' Raised Beach) sediments. The low resistivity area near Kersiepow was chosen for the site of the borehole (BH on Fig. 3), which penetrated to a depth of forty-five feet. The borer's log is given below, together with a list of the samples which were taken at intervals of about two feet. The samples were sealed in airtight jars as obtained.

TABLE I. **Auger Samples**

Auger Hole No.	Sample No.	Description	Depth at which sample was taken		Total depth of Augering	
			ft.	in.	ft.	in.
1	1	Silty clay	1	11	12	6
	2	Light grey clay with peaty material	4	6		
	3	Light grey clay	5	0		
	4	Sandy clay with pebbles	7	3		
	5	Sandy clay	8	2		
	6	Sand	12	4		
2	7	Yellow clay	1	8	6	9
	8	Yellow clay	2	6		
	9	Light bluish grey clay	3	6		
	10	Sandy clay	4	4		
	11	Sandy clay	5	0		
	12	Silty clay (bluish)	5	10		
3	13	Yellow clay	2	3	16	0
	14	Grey clay	5	10		
	15	Grey clay	9	5		
	16	Sand (brownish) and gravel	13	7		
	17	Sandy clay	15	4		
4	18	Silty clay (reddish)	2	0	8	6
	19	Grey clay	2	6		
	20	Sand	7	0		
5	21	Coarse clay with fine gravel	2	5	15	0
	22	Clay with peaty material	5	8		
	23	Sandy clay and gravel	8	8		
	24	Sandy clay	11	6		
	25	Blue clay	14	0		
	26	Blue clay	14	9		
6	27	Grey clay	2	8	12	0
	28	Sand and mud	6	1		
7	29	Boulder-clay (yellowish and sandy)	2	1	9	0
	30	Boulder-clay (yellowish and sandy)	3	10		
	31	Boulder-clay (yellowish and sandy)	6	0		
	32	Boulder-clay (yellowish and sandy)	7	0		
	33	Boulder-clay (yellowish and sandy)	8	9		
8	34	Boulder-clay (reddish)	1	6	3	9
	35	Boulder-clay (reddish)	2	7		
	36	Boulder-clay reddish)	3	4		
	37	Boulder-clay (reddish)	3	8		

Borer's Log of Borehole at Kersiepow

Deposit	Thickness ft. in.	Progressive depth ft. in.
Soil	1 0	
Laminated clay	11 6	12 6
Gravel	5 6	18 0
Sand and fine gravel with thin bands of clay	8 0	26 0
Silty clay (grey)	7 6	33 6
Silty clay (brown)	11 6	45 0

(Borers: David Pollock & Co. Ltd.)

TABLE II. **List of Borehole Samples**

Sample No.	Description	Depth at which taken (feet)
38	Silty clay	4 to 5
39	Blue clay with peaty material	7
40	Sandy clay and gravel	14
41	Gravel and fine sand	14 to 16
42	Sandy clay	24 to 25
43	Grey clay	27
44	Grey clay	29
45	Grey clay	31
46	Grey clay with brownish streaks	33½
47	Grey clay with brownish streaks	36 to 37
48	Grey clay with brownish streaks	39
49	Greyish brown silty clay	40
50	Greyish brown silty clay	41 to 42
51	Greyish brown silty clay	43
52	Greyish brown silty clay	44
53	Greyish brown silty clay	45

6. PHYSICAL PROPERTIES OF THE SEDIMENTS

Certain physical properties of the borehole and auger samples of carse clays, late-Glacial clays and boulder-clays were determined, and the mineral composition of the clays was estimated. Table III summarises the experimental work done on these deposits.

The physical properties were determined in order to define the sediments in terms of quantitative data, using standard methods of Soil Mechanics. The results are summarised in Table IV. The liquid limit determinations were made with the apparatus described by Casagrande (1932). The size-frequency distribution of particles in the samples was obtained (i) by sieving (down to a particle size of .076 mm.); (ii) by the pipette method (for particles between .076 and .002 mm.); and (iii) all particles less than

.002 mm. were grouped as clay fraction. Mechanical analysis results are given in Table V. In estimating the organic content of samples, material passing a No. 8 B.S. sieve was treated with hydrogen peroxide and dilute hydrochloric acid, to remove organic matter and calcium carbonate; the percentages of organic and acid soluble material found in this way were lowest in the late-Glacial clays.

TABLE III. **Summary of Tests**

	Carse deposits	Boulder-clays	Late-Glacial	Total
Total No. of samples	32	9	12	53
Moisture content determinations ...	30	9	12	51
Liquid limit values	21	7	10	38
Plastic limit values	19	7	8	34
Mechanical analysis	9	6	8	23
Differential thermal analyses ...	8	7	7	22
X-ray photos of clays	7	6	6	19
Salinity determinations	9	6	8	23

The experimental data given in Table IV show that, in general, (i) the liquid limits are higher than moisture contents, and (ii) plastic limits are lower than moisture contents, for samples except those from the carse deposits which are relatively sandy; (iii) the liquid limit is more sensitive to changes in lithological character in the sediments than the plastic limit.

TABLE IV. **Moisture Content and Atterburg Limits**

	Carse deposits	Boulder-clays	Late-Glacial sediments
Number of samples[1]	27	9	12
Natural moisture content, range ...	16 to 77%	15 to 27%	26 to 35%
Natural moisture content, average	39	18	30
Liquid limit, average	51	31	37
Plastic limit, average	25	18	18
Plasticity Index (av.) (=L.L.—P.L.)	23	14	20
Liquidity Index (av.) (=(W—P.L.)/P.I.)	0.56	0.18	0.65

[1] Excluding three peaty samples, with moisture contents over 100%.

A classification of fine-grained soils has been made by Casagrande (1947) based on the liquid limit and plasticity index, and taking into account the organic content of the sediments. On this basis, the late-Glacial clays and boulder-clays among the Devon Valley sediments fall into the group of inorganic clays. Most of the carse clays fall outside that group because of

TABLE V. **Composition of Samples**

(M.I.T. Grade Scale)

CARSE DEPOSITS Sample Nos.	3	5	8	12	15	17	19	26	40
Gravel (over 2 mm.)	—	14	1	—	—	12	—	3	— %
Sand (2 to .05 mm.)	23	45	3	27	8	50	27	19	47
Silt (.05 to .002 mm.)	59	33	53	46	66	31	55	67	36
Clay (below .002 mm.)	18	8	43	27	26	7	18	11	17
BOULDER-CLAYS Sample Nos.	30	31	33	35	36	37			
Gravel	1	4	21	21	29	18	%		
Sand	60	34	44	42	43	41			
Silt	32	41	24	25	16	31			
Clay	7	21	11	12	12	10			
LATE-GLACIAL CLAYS Sample Nos.	42	43	45	46	48	49	50	52	
Gravel	4	—	—	—	—	—	—	—	%
Sand	54	22	16	23	14	21	14	20	
Silt	32	53	62	61	68	66	69	62	
Clay	10	25	22	16	18	13	17	17	

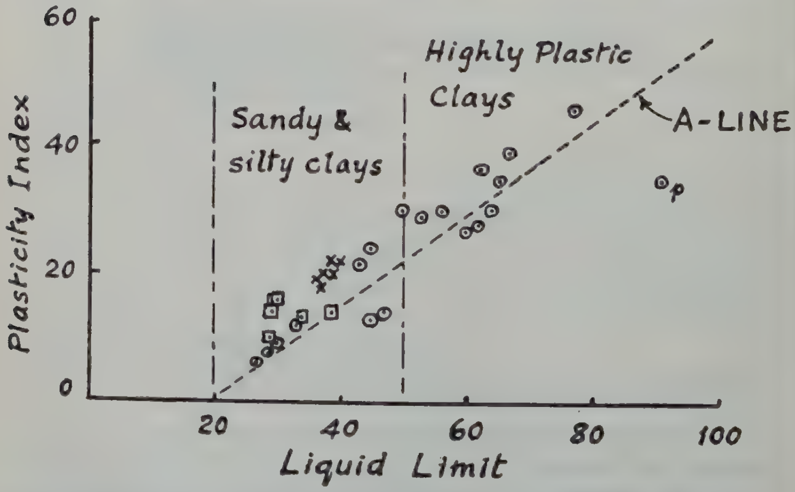

Fig. 5. Relation between plasticity index and liquid limit for samples from the Alva area. Carse deposits shown by circles, late-Glacial clays by crosses, boulder-clays by squares. Peaty sample marked p

their higher organic content. If further subdivisions are considered, some of the carse clays are highly plastic, and others are sandy clays (Fig. 5). The boulder-clays and late-Glacial clays plot in the group of sandy and silty clays. These results agree with the size analysis data referred to below. Points obtained by plotting liquid limit against plasticity index fall on straight lines approximately parallel to the A-line of Casagrande, indicat-

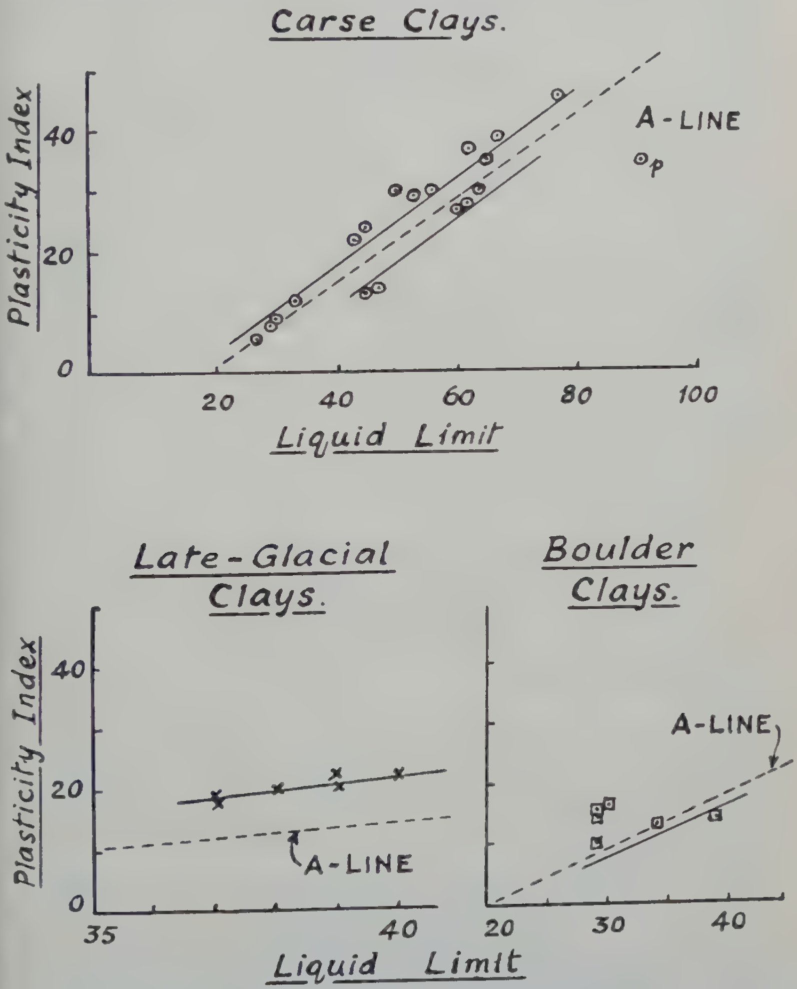

Fig. 6. Plot of plasticity index and liquid limit values, showing relation to A-line of Casagrande, for three groups of deposits

ing that the sediments of each group are of similar geological character (Fig. 6).

The cumulative curves plotted from mechanical analysis data are not reproduced here, but Table V summarises the results. The size-frequency distribution for late-Glacial clays is uniform, and the clays are characterised by a high percentage of silt (except No. 42); while the boulder-clays have a higher content of sand and gravel. The carse deposits show considerable variations, in contrast to the uniformity of the late-Glacial clays.

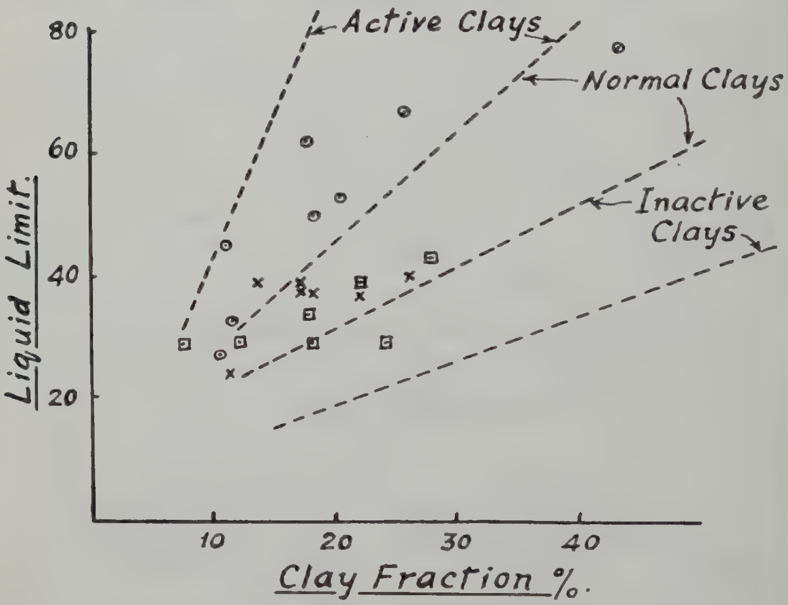

Fig. 7. Relationship between liquid limit values and percentage clay fraction of samples. (Ornament as for Fig. 5)

A study of Baltic sediments by Gripenberg (1939), which included both late-Glacial and post-Glacial deposits, showed the former to be better sorted and poorer in organic content. The Devon Valley sediments are similar to the Baltic sediments in this respect, but contain a higher proportion of coarse particles.

In Fig. 7 the amount of the clay fraction in samples, given in Table V, is plotted against liquid limit, and lines indicating the divisions for active, normal and inactive clays according to Skempton (1948) are shown. The late-Glacial clays fall into the field of normal clays, with one point in the active clays field. Boulder-clays plot in the range of normal and inactive clays. Of the carse samples, three fall in the field of normal clays and the rest in active clays; the higher organic content of the carse deposits, giving a higher liquid limit, would account for their presence in the latter group.

The data relating to plasticity index and percentage clay fraction, plotted in Fig. 8, are significant in estimating the mineral composition of the clays. The figure shows the values of 'activity' for illite (0.88) and montmorillonite (1.75), and all but one of the Devon Valley samples lie within the fields allotted to those minerals and away from kaolinite (0.41). The data suggest that the boulder-clays probably contain chiefly illite, while the late-Glacial and carse clays are likely to be mixtures of illite with some montmorillonite. Carse clays which plot close to the line defining Ca-montmorillonite may be rich in that mineral; or their high plasticity index could be due to a high liquid limit which in turn would result from their content of organic material. These results, therefore, give an indication of

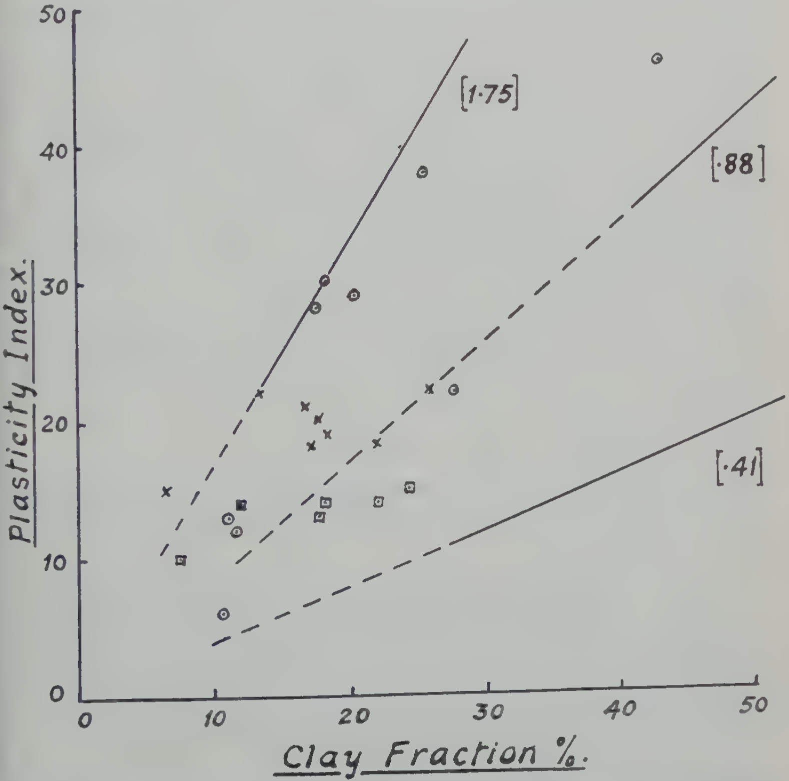

Fig. 8. Relationship between plasticity index and percentage clay fraction of samples. Numbers in brackets refer to the activity (= plasticity index/clay fraction). (After Skempton, 1953)

mineral composition, but more definite information was obtained by differential thermal analysis and X-ray methods.

7. DIFFERENTIAL THERMAL ANALYSIS AND X-RAY STUDIES

Differential thermal analyses were made on 22 samples (Table III, p. 41); the curves obtained are not printed here, but are given by the first author (Parthasarathy, 1954), and the results are now summarised.

The clay fractions of the Devon Valley sediments come from naturally occurring deposits, and it is reasonable to expect them to be made up of more than one clay mineral. Grim (1953) has pointed out that intimacy of mixing is an important factor to be considered when the identity of clay minerals in soils and sediments is determined from differential thermal curves. The thermal reactions of individual clay minerals in such mixtures are less sharp and changes occur in the positions of peak temperatures. The curves for the Devon Valley sediments indicate that more than one clay mineral is likely to be present in the fractions examined.

The D.T.A. curves are all similar, and all show a major endothermal peak at about 504° C., which is an important point for comparisons. This peak agrees with that observed for illites in other clays. From a careful analysis of the curves, and after comparing them with the known temperature ranges and peak temperatures of clay minerals, chlorites and hydrous oxides of iron and aluminium, the following conclusions were reached as to the mineral content of the clay fractions examined:

(a) In the carse deposits the clay fraction is chiefly made up of illite. The presence of small amounts of chlorites, montmorillonite and hydrous iron and aluminium oxides is also suggested, but there is no indication of the presence of kaolinite in appreciable amount. It is not, however, excluded as a minor constituent.

(b) In the boulder-clay samples, peak temperatures in the reactions again indicate chiefly the presence of illite, possibly together with very small amounts of minerals such as chlorite, montmorillonite, hydrous iron-oxide and kaolinite.

(c) In the late-Glacial clay samples, prominent endothermic reactions due to loss of structural water take place in the temperature range of 400 to 600° C., with a peak of 507° C., and it is probable that illite is the chief mineral of these clays. Kaolinite and montmorillonite are not present in any appreciable amount, but there may be a small content of the hydrous oxides of aluminium and iron, or of chlorite.

X-ray Powder Photographs

From a series of 19 powder photographs (Table III), values of *d* were calculated for strong lines, and interpretations were also based on comparisons with the powder patterns of standard minerals and with published data.

(*i*) *Carse Clays.* The photographs show strong lines at 4.5, 3.38 and 2.60Å, which are attributed to illite, since these values are not characteristic of minerals in the kaolinite and montmorillonite groups. Some of the weaker lines, however, agree with the *d*-values of chlorite and kaolinite, and suggest the presence of minor amounts of those minerals.

(*ii*) *Boulder-Clays.* Strong lines occur at 3.37, 3.39, 2.56 and 2.61Å, again indicating illite as the main mineral. Study of the powder patterns and *d*-values for weaker lines, however, suggests the presence of small amounts of kaolinite and chlorite, with kaolinite rather more plentiful than in the carse deposits.

(*iii*) *Late-Glacial Clays.* Here the strong lines appear at 3.39, 3.4, 2.62, 2.60, 2.58Å and are indicative of illite. Very small amounts of chlorite, kaolinite and montmorillonite may be present.

Further, samples of the clay fractions were treated with glycerol before being photographed: the characteristic lines for montmorillonite were absent, but weak lines at 2.92, 3.02, 3.51 and 3.53Å may be accounted for by assuming the presence of very small amounts of the mineral.

The interpretations were based on *d*-values less than 10Å. But some of the first order reflections corresponding to lattice spacings of around 20 kX, which are useful in the recognition of clay minerals, could not be obtained with the apparatus used (Unicam 9 cm. powder camera). The results of both X-ray and D.T.A. methods compare favourably and indicate the probable clay mineral content of samples.

8. SALINITY TESTS

Tests were made in order to determine the amount of salt in the pore water of the sediments, especially as the low resistivity associated with the late-Glacial deposits suggested their possible saline nature. The results are shown in Table VI.

In the late-Glacial clays there is a tendency for salinity to increase with depth. The deepest sample, obtained from forty-five feet below ground-level, has a salt concentration of 12.69 gms./litre. From the values of salinity and water content for the various samples, their resistivities can be calculated (Sundberg, 1932). The resistivity values thus obtained were in general accordance with those obtained from field observations; but detailed comparisons cannot be made because the field observations give in effect an average resistivity, and are affected by higher resistivity layers near the surface.

TABLE VI. **Salinity Content**

CARSE CLAYS		BOULDER-CLAYS		LATE-GLACIAL CLAYS	
Sample No.	Salt conc. in gms./litre	Sample No.	Salt conc. in gms./litre	Sample No.	Salt conc. in gms./litre
3	0.144	30	0.55	42	1.63
5	0.341	31	0.465	43	2.34
8	0.182	33	0.24	44	4.8
12	0.433	35	0.605	46	6.49
15	0.366	36	0.75	49	6.43
17	0.652	37	0.66	50	6.83
19	nil			51	8.47
26	0.363			52	12.69
40	0.169				

9. CONDITIONS OF SEDIMENTATION

From a correlation of the physical data found experimentally and the estimated mineral content, an attempt can be made to postulate the environmental conditions during the deposition of the late-Glacial and carse deposits. It is the late-Glacial clays that form the bulk of the superficial deposits in the buried valley of the Devon, and their mode of deposition is of primary importance. As already stated, these deposits were formed in the seas that invaded the area, following the retreat of the glaciers and the removal of the ice load from the land. The data suggest that the deposits were formed under estuarine conditions rather than in an off-shore environment. The problem as to the kind of estuary, whether of the coastal type or of the fjord type, is next considered.

Pritchard (1952) has defined an estuary as ‘a semi-enclosed coastal body of water having a free connection with the open sea and containing a measurable quantity of sea salt’. In his study of the coastal estuaries connected with the open ocean, he has observed a tendency for a general decrease in salinity from the mouth to the head of the estuary, due to the infiltration of fresh water near the land. If such conditions had existed in the Devon Valley area, with the head of the estuary nearer Tillicoultry and the mouth farther west near Cambus (three miles east of Stirling), there is the possibility of an increase of salinity towards Alva. Secondly, from Lacaille’s figure showing the limit of extension of the arm of the ‘100 foot’ Sea inland, it can be seen that nearer Tillicoultry there is a greater chance of admixture of fresh water.

In favour of a fjord type of estuary there is the evidence of a hollow, extending to a depth of about 350 feet, near Kersiepow, with depths becoming somewhat shallower towards Tillicoultry and Alva. This suggests a basin-shaped structure with a sill-like entrance from the open ocean farther west, with which the basin may be regarded as having been connected. If this conception is true, it carries with it the possibility of deposition under saline conditions. There is not much evidence for stagnant fjord conditions, as the organic content of the late-Glacial sediments is very low. The relatively higher carbonate contents as found from laboratory tests on these deposits may also then be explained: sediments formed under fjord conditions contain appreciable amounts of carbonates and are usually saline, varved, and laminated (Fleming & Reville, 1939). Deposition in quiet waters, as suggested for the late-Glacial sediments by several writers, is also understandable in the light of restricted fjord-like estuarine conditions as envisaged here.

Because of the restricted area of the geophysical survey in the Devon Valley it is difficult to decide whether the environment in which the late-Glacial deposits were formed was a normal estuary or a fjord, but the latter is favoured on the balance of evidence. The uniform nature of the late-Glacial deposits, their high salinity, the predominance of illite (with small amounts of chlorite, kaolinite and montmorillonite), all point to such a conclusion. The presence of large amounts of kaolinite would have indicated acid, lacustrine conditions. This mineral not being present to an appreciable extent suggests either marine or salt lagoon conditions (Millot, 1952). Highly saline waters such as might occur under acid conditions are not advocated, as neither a total absence of kaolinite nor an abundance of montmorillonite is met with.

The Devon Valley carse deposits, regarded as of marine origin by earlier writers from fossil evidence, are now found to have a low salt content, but the absence of marked salinity can be due to subsequent leaching of the sediments (cf. Rosenquist, 1955). Being quite near the surface they may have been affected by the percolation of ground-water. The carse clays have also been found to be rich in organic content, with an admixture of peaty material. Milder climatic conditions at the time of deposition may have accounted for the organic detritus.

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The Geology of the Devonian and Carboniferous Rocks of the North-West Border of the Dartmoor Granite, Devonshire

by W. R. DEARMAN and N. E. BUTCHER

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ABSTRACT: A stratigraphical succession of four lithological series has been established within the country rocks bordering the north-west corner of the Dartmoor granite mass. Upper Devonian Slates crop out to the south of the main Culm Measures boundary whilst to the north a series, in part of Famennian age, occurs as inliers in the Culm Measures. This series, here termed the Transition Series, is gradational in lithology between the Upper Devonian Slates and the Lower Culm Measures. The Lower Culm Measures, which are succeeded with a marked change in lithology by the Upper Culm Measures, occur in two main outcrops, and each is followed to the north and south by the Upper Culm Measures. Facies changes have been recognised in both divisions of the Culm Measures.

Dolerite dykes and sills, with some spilitic lavas and pyroclastic deposits, are virtually confined to the Lower Culm. Sills in the southern outcrop were probably emplaced before the deposition of the Upper Culm sediments.

The structures have been divided into four major units which show a progressive change in fold attitude from south to north. The pre-granite structural pattern over the whole area comprised recumbent zig-zag folds broken by normal strike faults parallel to the bedding in the folds. These normal faults dipped at low angles to the north and south. The continuous north–south horizontal elongation implied by this structural pattern was maintained by later basic dyke injection in the north and by the emplacement of the granite, with jointing and granite dyke intrusion. The granite pushed aside and lifted up the previously recumbent folds, and in the process reactivated the normal faults dipping to the north. The structural units are now bounded by these major normal faults.

Contact metamorphism and metasomatism by the granite induced mineralogical changes in the sediments and the associated igneous rocks.

Both the granite and the country rocks are cut by a system of breccia-faults.

1. INTRODUCTION

THE AREA to be described comprises a narrow strip of country rocks, some two to three miles wide, which borders the north-west corner of the Dartmoor granite mass in Devonshire. It extends for twenty miles from South Tawton on the north to Tavistock on the west of the granite (Fig. 1).

Sedgwick & Murchison (1840) recognised the Carboniferous age of the central deposits of Devonshire, which they called the 'Culm Measures', and referred all the rocks of the main outcrop south of the line indicated in Fig. 1 to the Lower Culm Measures. To the north of this line lay the extensive outcrop of the Upper Culm Measures. On the map accompanying his classic memoir De la Beche (1839) showed the distribution of igneous rocks in the sediments.

Holl (1868) added to the valuable detailed descriptions of these earlier geologists and gave a particularly good account of the structural effect of the Dartmoor granite on the country rocks.

The works of Allport (1876) and Rutley (1878, 1880) on the igneous rocks associated with the sediments, and on their contact metamorphism by the granite, constitute some of the earliest accounts in microscopical petrology.

Ussher, whose main papers were in 1892, 1900 and 1901, undoubtedly made the greatest contribution to the study of the Culm Measures. He subdivided the Upper Culm of Sedgwick & Murchison into Middle and Upper Culm and recognised in the area under consideration the presence of both Lower and Middle Culm with Devonian inliers, although on his quarter-inch map (1901) he did not distinguish between the Lower and Middle Culm. The two-fold classification of the Culm Measures by Sedgwick & Murchison will be used here. Ussher also appreciated the presence of zig-zag folds, and the inversion and repetition of the strata to the west of Dartmoor. Hinde & Fox (1895, 1896) made an important contribution to stratigraphical knowledge of the Culm Measures by recognising the radiolarian character of beds in the Lower Culm. Radiolaria were found by them at several localities in the present area.

The work of the Geological Survey in the Petertavy district (Reid &

others, 1912, in explanation of the One-Inch Sheet 338) saw a reversion to the interpretation of Sedgwick & Murchison (1840). All the rocks in the Culm Measures were referred to the Lower Culm.

R. H. Worth in 1919 gave a detailed account of the geology of the Meldon area near Okehampton, adopting a succession which did not take into account overfolding with consequent repetition of strata. Worth's succession was later accepted by Osman (1924) in a description of the Whiddon Down area to the east of that to be described here (Fig. 1). In 1923 Sherlock, one of the authors of the Dartmoor Memoir of the Geological Survey, wrote an account of the geology of the southern district for a Field Meeting of the Geologists' Association held in 1922.

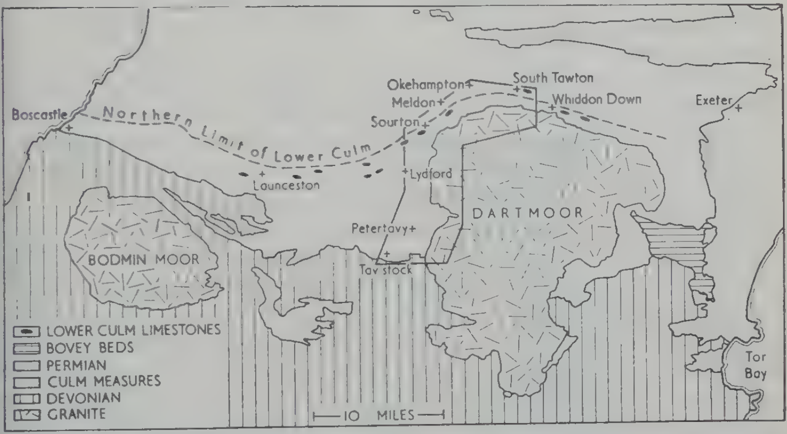


Fig. 1. The geological setting of the area showing the relationship to the Dartmoor granite and the southern boundary of the Culm Measures trough of central Devon. Boundaries after the Geological Survey

The present investigation was started by one of us (W.R.D.) in the northern Okehampton district, the area around Meldon with excellent quarry exposures providing a type for the succession and structure of the local Culm Measures (Dearman, 1958). The work was later extended southwards, the Petertavy district being mapped by N.E.B., whilst the intervening Lydford area and the preparation of this paper has been a joint responsibility.

A detailed stratigraphical succession is shown accompanying the map forming Fig. 14. It is presumed that the oldest rocks in this area are the Upper Devonian Slates which crop out to the south of the Culm Measures at Tavistock. Three lithological series have been recognised to the north of these slates; these are the Lower and Upper Culm Measures, and an older series proved in part to be of Upper Devonian, Famennian age, which is found as inliers within the Culm Measures. Igneous dykes and sills, with some lavas and pyroclastic deposits, are virtually confined to the Lower Culm Measures.

Zig-zag folding has determined the structural pattern of the whole area, and the bedding plane slip movements assumed to be involved in the generation of these folds were continued in a later strike-faulting phase of deformation. Along the northern margin of the granite the angular folds are now overturned to the south, but they change to recumbent zig-zag folds as the structures are followed south-westwards along the strike to beyond the area mapped. This recumbent attitude, but with a low westerly plunge, is also the characteristic structure along the western side of the granite. The present variable attitude of the folds suggests that the Dartmoor granite was emplaced by the pushing aside and uplifting of the country rocks.

The area has been divided into four structural units; a Foundation Unit of Upper Devonian Slates to the south of Tavistock is overlain successively northwards by three units of distinctive structural pattern, the Petertavy, Lydford and Meldon Units. These are complex zig-zag structures separated by major normal faults dipping at low angles to the north.

The granite mass is a composite intrusion (Brammall & Harwood, 1923); coarse-grained porphyritic biotite-granite forms a marginal facies which is invaded by flat-lying sheets of finer-grained non-porphyritic to feebly porphyritic granite. The finer-grained variety has so far been mapped only in the northern part of the area (Fig. 14). The petrography of the granite is beyond the scope of this paper. The approximate outer limit of the contact-metamorphic aureole is shown on the map. Both the granite and the country rocks are cut by a system of late breccia-faults, the most important of which trend between north-west to south-east and north to south.

The north-west corner of the Dartmoor granite mass rises to 2000 feet, and from these heights the main rivers flow in a radial pattern. Deeply dissected valleys within the contact-metamorphic aureole on the north-western margin of the granite provide almost continuous exposures, whereas in the southern part of the area the valleys are wider and afford fewer exposures. The three outcrops of the Upper Culm Measures which lie within the aureole are associated with high bare moorlands, in contrast to the cultivated areas underlain by the older rocks.

In this paper the registration numbers of fossils in the collections of the Geological Survey Museum are referred to by the abbreviation 'GSM', those in the British Museum of Natural History by 'BM'. All National Grid reference numbers occur within the 100 kilometre square 20 (SX).

The following terminology is adopted. Words and phrases such as 'pass up (or down)', 'overlain by' or 'underlain by', 'upper' and 'lower' refer only to present attitude and therefore not necessarily to the correct order of stratigraphical succession. 'Succeeded by', 'top' and 'bottom' refer only to the direction of proven younger and older beds. The symbol 'Y' indicates the direction of 'younging' of the strata. 'Foliation' is used as a purely descriptive term for parallel planes which may be either bedding or cleavage. 'Shear cleavage' refers to cleavage planes along which small offsets of the bedding occur, usually less than one-half inch.

2. THE STRATIGRAPHICAL SUCCESSION

The stratigraphical succession has been established with the aid of limited palaeontological evidence and sedimentary structures. Part of the older series found as inliers within the Culm Measures has been proved by ammonoids and trilobites to be of Famennian age, the *Platyclymenia*, *Clymenia* and possibly also the *Wocklumeria* Zones being recognised. Part of this palaeontological evidence has been obtained from three localities which lie immediately west of the area so far mapped (Fig. 14).

This series appears to correspond with what has previously been called the 'Petherwin Beds' (Reid & others, 1911), the name given to cover a large number of separate outcrops between the Bodmin Moor and Dartmoor granites. It does not seem desirable in this case to use a name derived from a particular locality. Moreover, Selwood (1958) has recently redefined the Petherwin Beds to cover only the strata exposed near South Petherwin, one mile south of Launceston, where the beds are of *Platyclymenia* and *Clymenia* Zone age. It seems clear that the equivalents in our area of the redefined Petherwin Beds form only a part of this series.

In the area to be discussed in this paper the series, taken as a whole, is transitional in lithology between the Upper Devonian Slates and the Lower Culm Measures. We propose to name it the 'Transition Series', because of this gradation in lithology.

Posidonia becheri, suggesting the Upper Viséan, has been found in the highest beds of the Lower Culm Measures at a number of localities (Fig. 14) in the northern part of the area. The Lower Culm Measures are quite distinct in lithology from the succeeding Upper Culm Measures.

Each of the four series, the Slate Series, the Transition Series and the Lower and Upper Culm Measures, is subdivided into groups which are given local names. Reliable estimates of the thicknesses can only be made for the lithological subdivisions of the Lower Culm Measures in the Meldon area (Dearman, 1958). Thicknesses of the other groups are unknown.

(a) The Upper Devonian Slate Series

The Whitchurch Green Slates. This monotonous group of grey-green slates and phyllites forms part of the extensive outcrop of Purple and

Green Slates stretching from the north Cornish coast to south-east Devon. House (1956) has shown that in the Padstow area the series yields *Gephuroceras* and is therefore at least in part of Frasnian age. Fossils have not been found near Tavistock, although the Survey (Reid & others, 1912, 8) noted 'traces of a trilobite'.

(b) The Transition Series

Strata now included in the Transition Series were first recognised in the Railway Quarry (568927) at Meldon where it was realised that a narrow faulted band of slates with associated lenticular beds was older than the surrounding Lower Culm (Dearman, 1958). Subsequently, similar rocks were found to have a considerable outcrop in the valley of the River Lyd, where, in contrast to Meldon, they are bordered to the north by Upper Culm Measures and to the south by a very narrow band of Lower Culm Measures.

Farther to the south, a very small inlier of this series has been recognised at Marytavy (505792) purely on palaeontological evidence. This inlier is situated close to a junction between Lower and Upper Culm.

The remaining strata so far included in this series occur at three fossiliferous localities just to the west of the present map (Fig. 14) and their extent and relations to surrounding rocks have not yet been ascertained. These localities are near South Brentor (480806), near North Brentor (480809), and in the stream (502832) north of the Manor Hotel, near Lydford Station.

The Transition Series comprises slates with silty and calcareous beds, the Meldon and River Lyd Groups being distinguished by a marked development of lenticular bedding. At the South Brentor locality a distinctive calcareous siltstone–shale lithology is found, and this has also been recognised within the aureole of the granite at horizons in the Meldon and River Lyd Groups (Plate 2).

(*i*) *The Manor Hotel Beds*. The oldest beds of the Transition Series so far recognised are those in the stream (502832) north of the Manor Hotel near Lydford Station. Here, in grey to purple slates with a one foot thick bed of fine-grained dark-grey limestone close by, Dr. M. R. House found in April 1957 several small specimens of ? *Imitoceras* sp. (GSM Zi 8331–4) which occur as pyritised moulds. Recently, in September 1958, one of us (N.E.B.) found, associated with these forms, a small coarsely-ribbed ammonoid. Professor F. Hodson has kindly identified this as *Platyclymenia* (*Pleuroclymenia*) sp. which therefore indicates the Famennian *Platyclymenia* Zone.

It is worth noting that near by, in the shallow railway cutting (503833) on the line from Lydford to Bridestowe, an exposure in green slates yielded to the Survey geologists 'a fenestellid, crinoidal columnals, *Ambocoelia urei* (Flem.), *Spirifer verneuili* ? (Murch.)' (Reid & others, 1912, 8).

(*ii*) *The Marytavy Beds*. In the bank of the stream (505792) 680 yards north-west of Marytavy Church, the Survey noted 'a little, very hard and sheared, micaceous killas in contact with black killas, and the junction of the two is most probably a fault or thrust' (Reid & others, 1912, 8). The micaceous killas yielded a single ammonoid which was referred to the genus *Brancoceras*. Professor H. Schmidt has kindly identified this specimen (GSM 57362), from preparations supplied by Dr. House, as *Imitoceras sulcatum* (Münster) and notes that this species is commonest in the *Clymenia* Zone of the Famennian. The exposure is a poor one, and consists of a strike section through six feet of soft blue-black slates overlying a completely decomposed concordant igneous intrusion, of which only the upper foot is exposed. Confirmation that it is the overlying slates at this locality which yielded the Survey specimen has been obtained by Dr. House who found indeterminable ammonoids in sparse nodules in the slates.

(*iii*) *The South Brentor Beds*. There are two closely spaced quarries (480806) 400 yards north of South Brentor Farm. Fifteen feet of thinly bedded black calcareous siltstones, interlaminated with shale, and dipping north-easterly at 25°, are exposed in the western quarry. The siltstones are composed of angular to sub-angular quartz grains, with a maximum grain size of 0.1 mm., set in a calcite matrix (Plate 2, A). These beds are overlain in the eastern quarry by an apparent thickness of ten feet of finely laminated black slates which, in the extreme northern corner of the quarry, appear to pass up into grey-green slates with nodules. Thus there is a distinct colour change from black to green in the rocks of the two quarries, but in the absence of diagnostic sedimentary structures it is not known whether the green slates are the youngest beds.

The Survey recorded (Reid & others, 1911, 12) from this locality a few lamellibranchs *in situ*, and ostracods, a coral and a brachiopod found loose in tuff which has not been found in place. The lowest beds of siltstones and shales were found by us to contain poorly preserved brachiopods and lamellibranchs, whilst the overlying black slates yielded abundant lamellibranchs and a few indeterminable ammonoids. Dr. W. H. C. Ramsbottom and Mr. J. D. D. Smith have kindly identified the following genera: ?*Leptodesma*, *Myalina*, ?*Mytilarca*, *Paracyclas* and *Posidonia* (GSM Zi 8335–8362).

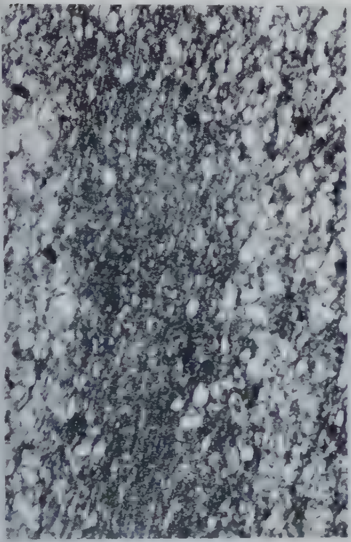
Dr. House subsequently proved that the uppermost horizon of grey-green slates with nodules contains a fauna comprising ammonoids, trilobites, brachiopods, ostracods and corals. *Cymaclymenia* sp. (GSM Zi 8323) has been found by him *in situ*, whilst *Imitoceras* sp. (GSM Zi 8324–5) and *Sporadoceras posthumum* (Wedekind) (GSM 87113–5) have been found loose in waste from this quarry. This ammonoid fauna suggests the *Clymenia* Zone. Of the trilobites, Dr. R. Goldring has kindly identified *Phacops* (*Cryphops* ?) *wocklumeriae* R. and E. Richter and *Phacops* (*Phacops*) *granulatus* (Münster) which indicate either the *Clymenia* or the *Wocklumeria* Zone.

(*iv*) *The North Brentor Beds*. At 350 yards north of the South Brentor quarries is a small quarry (480809) exposing eight feet of green slates with rare nodules. In a pile of loose blocks close by the exposure one of us (W.R.D.) found in March 1956 a block showing an ammonoid, the lithology matching that of the exposure. On subsequently breaking down this block Dr. House identified *Kosmoclymenia* sp. cf. *undulata* (Münster) (GSM Zi 8329–30) and indeterminable clymenids (GSM Zi 8326–8). Two poorly preserved ammonoids were noted in disintegrating 'gingerbread'; one, less than eight millimetres in diameter, was tentatively referred to ? *Wocklumeria* and the other was thought to be ? *Sporadoceras*, but both records need confirmation. Hence there is the possibility that these beds represent some part of the *Wocklumeria* Zone, the top-most zone of the Upper Devonian.

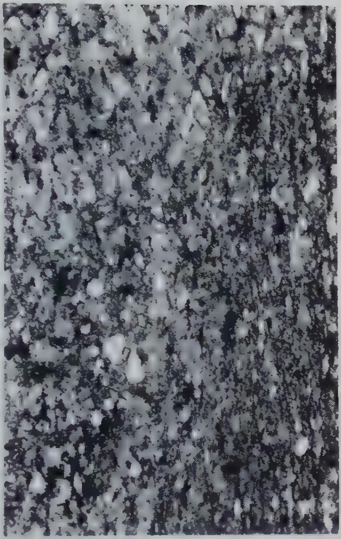
(*v*) *The Meldon Slate-with-Lenticles Group*. This group consists of alternations of dark-brown slates and thinly bedded or lenticular green coarse siltstones within the contact-metamorphic aureole of the granite. Where cleavage is absent they become tough banded green and brown hornfelses. The green siltstones consist of angular detrital quartz set in a matrix of green amphibole derived from the original calcareous cement (Plate 2, B).

(*vi*) *The River Lyd Slate-with-Lenticles Group*. The essentially uniform nature of this group is well displayed in the numerous exposures in the valley of the Lyd. In their unmetamorphosed state they are seen to consist of grey to black slates in which rapid alternations of silty beds and occasional calcareous beds are developed. These latter vary from apparently continuous sheets with a thickness of about half to one inch to distinct lenticles which are usually some six inches in length and half an inch in thickness as seen in cross section. Within the aureole these beds are similar to the Slate-with-Lenticles Group in the Railway Quarry at Meldon.

In the railway cutting (517854) at Lydford slates with lenticles of cross-laminated siltstone are seen to pass up into shales with hard fine-grained siliceous beds. There is one horizon of thinly banded green and brown contact-altered calcareous siltstones which is also exposed in a nearby quarry (515854) where traces of fossils were seen. In thin section these striped beds have the distinctive siltstone–shale lithology (Plate 2, C) seen in the South Brentor Beds; and here, as at Meldon, the original calcareous cement is replaced by green amphibole. A massive siltstone, two feet thick, is exposed in this Lydford quarry.



A



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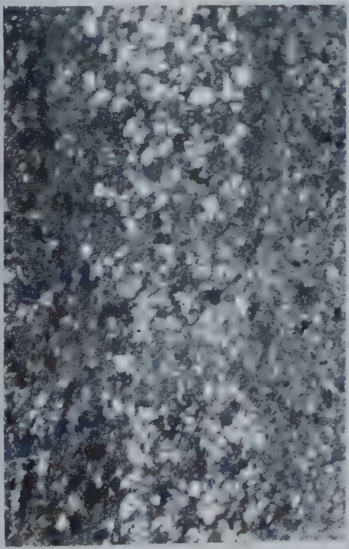

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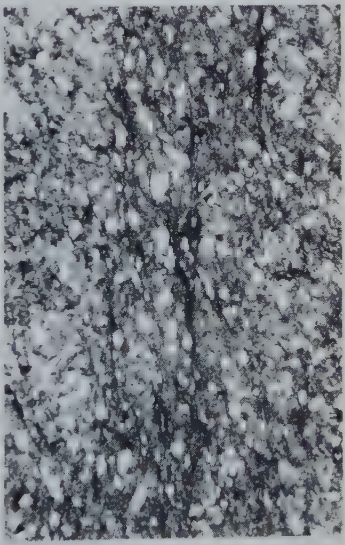


D

This distinctive siltstone–shale lithology has also been found on the southern side of this group in the railway cutting (502831) on the Launceston line just north of Lydford Station (Plate 2, D).

(c) The Lower Culm Measures

There are two main outcrops of the Lower Culm Measures, in the Meldon and in the Petertavy districts, and these are followed both to the north and south by Upper Culm Measures. In addition a narrow band of Lower Culm lies between the Transition Series and the Upper Culm south-east of Lydford.

The Lower Culm Measures have been divided by us into an older Shale-and-Quartzite Group and a younger Calcareous Group. Both groups contain interbedded pyroclastic deposits and radiolarian beds, and are subject to marked lateral variations. In the Meldon district concordant igneous intrusions are confined to the Shale-and-Quartzite Group, whereas in the Petertavy district a great number of intrusions occurs in both subdivisions of the Lower Culm. A few lava-flows are found near the top of the Calcareous Group in the vicinity of Tavistock. The base of the Lower Culm Measures has not been identified.

(*i*) *The Meldon Shale-and-Quartzite Group*. The rocks of this group are interlaminated shales and fine siltstones, and the Meldon occurrences may be taken as representative of the variations likely to be met anywhere in this northern district. At the bottom of the group in the Railway Quarry there are eighty-five feet of black chiastolite-slates; these pass by interlamination into forty-five feet of thinly bedded white and brown shaly quartzites which are succeeded in turn by 130 feet of massively bedded black shales at the bottom of the Volcanic Group.

The Volcanic Group forms a prominent horizon of pyroclastic rocks within the Shale-and-Quartzite Group, and is an accumulation of up to 200 feet of spilitic and keratophyric agglomerates, crystal-, lapilli- and dust-tuffs, and tuffaceous shales. Thin tuff beds may be graded or cross-laminated; but there are massive beds up to forty feet thick representing ash suspensions which were swept into the sites of deposition, disrupting in their passage the underlying sediments and incorporating large and small blocks of the partly compacted muds and silts. As a result of this activity some of the black shales and white or buff quartzites interbedded with the tuffs either break up when followed along the strike or have deep erosion furrows on their top surfaces. The Volcanic Group decreases in thickness in all directions from the Meldon centre.

These tuffs are succeeded by seventy feet of interlaminated shales and quartzites. Some quartzite laminae represent accumulations of closely packed radiolarian tests.

The Shale-and-Quartzite Group is thicker in the Red-a-ven Brook exposures. Here, in the 600 feet of predominantly shaly sediments, tuffs are fully developed, and chiastolite-slates do not form a definite horizon but are present as thin bands of hard chiastolite-mudstone scattered throughout the sequence. Similar variations are met elsewhere in the outcrop.

(*ii*) *The Hill Bridge Shale-and-Quartzite Group*. A non-calcareous group of Lower Culm sediments can be mapped within the aureole of the granite in the Petertavy district. Although poorly exposed, it is similar to the Meldon Group, and in the River Tavy and Youldon Brook it consists of hard black shales with thin interlaminations of fine-grained quartzite. The quartzite beds may attain thicknesses of approximately one foot.

(*iii*) *The Meldon Calcareous Group*. The sporadic distribution of limestone quarries in the outcrop of the Lower Culm from Launceston to beyond Whiddon Down, as illustrated in Fig. 1, suggests either that the limestones themselves may be large lenticular deposits or that these particular outcrops may have been determined by a combination of structure and topography.

A complete succession through the group is known only at Meldon. Here in 240 feet of strata limestones are predominant in the bottom 100 feet, are succeeded by interbedded black shales and radiolarian cherts, whilst limestones appear again in the top twenty feet. The older limestones have been worked on the banks of the West Okement River; the same beds high on the valley slope in the Railway Quarry are weathered to a depth of more than fifty feet to dark brown clays, whilst the associated radiolarian cherts have been reduced to non-plastic silts. A similar occurrence on the Red-a-ven Brook has been investigated by pitting, and it has been proved that the limestones pass laterally into cherts, and higher in the sequence cherts may also pass into black calcareous shales.

(*iv*) *The Watervale Calcareous Group*. The current Geological Survey One-Inch Sheet 338 shows two lenticular outcrops of calc-flinta in the Lydford district. The southern band can in fact be traced through to the granite, whereas the northern outcrop appears to be restricted (Fig. 14) as shown on the Survey map. These two outcrops are similar in field appearances, both consisting essentially of brown and green banded rocks, and it was thought (Dearman & Butcher, 1958) that they were equivalent in age.

However, microscopical study reveals significant differences between these two outcrops. The northern restricted outcrop is seen in thin section to comprise the distinctive calcareous siltstone–shale lithology, angular detrital quartz grains becoming obvious even with quite low magnifications, and these rocks therefore are not true calc-flintas at all (Barrow & Thomas, 1908). They constitute the horizon of altered calcareous siltstone in the River Lyd Group of the Transition Series discussed on page 58. This distinctive lithology has not been found anywhere in the southern outcrop.

The southern band is best exposed by the main road (518839) 300 yards north of Watervale, and consists of true calc-flintas with associated chiastolite-slates and flinty biotite-quartzites. They are not seen in their unaltered state. Elliptical quartz-mosaics, presumably representing radiolarian casts, are occasionally abundant. Since the evidence so far available from the whole area suggests that radiolarian beds are diagnostic of the Lower Culm Measures, the Watervale Group is here referred to this series.

(*v*) *The Tavistock Calcareous Group*. This group consists of interbedded black shales and hard siliceous beds. Hinde & Fox (1895, 1896) identified radiolaria from this group in the railway cuttings between Marytavy and Tavistock. Near the top of the sequence, in Tavistock itself, typical Lower Culm carbonaceous limestones are present which have not been previously recorded. The maximum thickness of these limestones is about twenty-five feet in Lower Deerpark Quarry (483743) where they vary from massive beds to poorly cross-laminated limestones. Crystal-lithic tuffs occur sporadically in this group, and thin graded tuffs are seen in Tavistock.

(d) The Upper Culm Measures

The Lower Culm Measures are succeeded by the Upper Culm with a marked change in lithology from calcareous to arenaceous beds, and this has provided boundaries which can be easily mapped.

There are two lithological facies within this series; coarse greywackes of the Whitchurch Down outcrop may be distinguished from the medium-grained sandstones of the more northerly outcrops. These may be equivalent in age and are presumably Namurian, but as yet no fossils other than sporadic plant debris have been found in the Upper Culm Measures in this district. During the last century Vicary collected goniatites from the Upper Culm at Itton Quarry (676989), three miles north-north-east of South Tawton, but these specimens (BM C 12801–4) have proved to be indeterminable.

(*i*) *The Whitchurch Down Greywacke Group*. An almost continuous section through this group is exposed on the River Tavy in Tavistock. Black, lustrous and fissile shales are interbedded with dark grey greywackes which are usually less than one foot thick. In the south-western end of the section graded bedding is an obvious feature of the greywackes with a maximum particle size of nearly one centimetre. There are exposed, immediately north of the footbridge (479741), some fifty feet of distinctive beds which are not seen elsewhere. These, associated with the normal shales and greywackes, consist of repeated units, usually less than three inches in thickness, of cross-laminated and graded fine greywacke material, the tops of the units comprising thin shale beds which frequently truncate the fore-set laminae of the older greywacke material.

The ill-sorted character of the greywackes can be seen in the field in the coarser-grained bottoms of the graded beds and thin sections confirm this distinctive feature of all the greywackes. Detrital quartz is accompanied by sodic plagioclase and occasional rock fragments, including igneous rocks, set in an argillaceous matrix. Small, pale rounded zircons are conspicuous in thin section.

Ussher (1903, 168) referred these rocks to his Middle Culm division, and compared them to the coarse-grained arenaceous beds exposed in Ugbrooke Park near Chudleigh on the eastern side of Dartmoor.

(*ii*) *The Black Down, Southerly Down and Okehampton Sandstone Groups*. The rocks of these three outcrops possess obvious similarities in lithology which stand in contrast to the Whitchurch Down Group. They consist of grey, micaceous poorly laminated shales interbedded with siltstones. Greenish-grey beds of medium-grained sandstone are present, usually less than two feet in thickness, the proportion of sandstone to shale and siltstone being variable. Small-scale cross-lamination is a constant and distinctive feature of these groups, and bottom structures—flute-casts and groove-casts—are frequently present indicating a general east–west current direction during sedimentation.

In thin sections the sandstones consist of well-sorted sub-rounded quartz grains with a maximum size of about one millimetre, crowded together in a sparse chloritic matrix. Small pale rounded zircons are, as in the Whitchurch Down Greywacke Group, a feature of the thin sections of these sandstones.

3. THE IGNEOUS ROCKS

There is a marked field association between the Lower Culm Measures and the distribution of igneous intrusions. This is well seen to the north-east of the Dartmoor granite in the Teign Valley area (see Sheet 339, and the quarter-inch map in Page, 1906). The Survey Sheet 338 suggests that this same association is to be found west of Dartmoor, since within the area of this map intrusions are mainly confined to the Petertavy district. The adjacent Black Down area is devoid of igneous rocks. It has been shown above that Lower Culm sediments crop out in the Petertavy district whereas Black Down is underlain by Upper Culm.

Two intrusions have been found in the Transition Series in our area. One has been identified at the exposure of the Famennian inlier at Marytavy (p. 57). This intrusion is presumably that referred to by Reid & others (1912, 8) as 'micaceous killas'. The habit of the iron ore in thin section reveals the igneous origin of this completely altered rock. The other intrusion is a small concordant metadolerite found within the River Lyd Group close to the granite margin (532859) north-west of Brat Tor.

A few intrusions have been found associated with the Upper Culm

Measures in the Petertavy district, and it is probably these to which Ussher (1901, 364) referred as penetrating the 'lower beds of the Middle Culm'. One small concordant mass occurs in the Whitchurch Down Group, faulted against the Upper Devonian Slates, in the River Tavy (478739) in Tavistock. In the Marytavy area there are some small, and one large, weathered intrusions which appear to be surrounded by the Black Down Group. It is not clear, because of the poor exposure, whether these in fact occur within, or have fault relations to, the Upper Culm.

The igneous suite in the Lower Culm consists predominantly of minor intrusions, most of these being concordant lenticular sheets. A few fine-grained masses have been found in the Petertavy district invading, and chilled against, earlier sheet intrusions, and these may occupy feeder necks. One lenticular sheet of porphyritic dolerite occurs in the Watervale Calcareous Group in the Lydford district.

The lenticular sheet intrusions show considerable differences between the Meldon and Petertavy district Lower Culm outcrops. These differences are in the extent of development, in detailed petrography, and also it is thought in time of emplacement. Of these differences, time of emplacement is the most important. Evidence is given that the intrusions in the Meldon district were emplaced generally along the bedding after the pre-granite deformation, but are earlier than the granite. These are referred to here as dykes. In the Petertavy district, on the other hand, the intrusions are thought to be fully involved in the pre-granite deformation, and are referred to as sills. These were probably emplaced before the deposition of the Upper Culm sediments.

(a) The Meldon District

Two types of basic intrusion have been found in the older group of Lower Culm Measures. The structural relations of both types have been determined in the Railway Quarry at Meldon where they form dykes emplaced along the steep bedding of the sediments as shown in Fig. 9. An ophitic albite-dolerite—the Dyke One facies—has prominent chilled margins, and follows a monoclinal bend with small fault offsets in the underlying sediments. The dyke has a wedge-shaped cross-section. The other dyke lies fifty yards to the south, and is a fine-grained albite-biotite rock with prominent albite phenocrysts—the Dyke Two facies—which rises along steep bedding. This dyke, too, presents chilled margins to the bedding, fault planes, and drag folds, and in early exposures was in contact with a major reverse fault plane.

On this evidence the dykes are later than the main phase of pre-granite deformation and similar sheets were emplaced at the same time along the flat bedding in the overfolds.

(b) The Petertavy District

Sills are present throughout the outcrop of the Lower Culm Measures in this district. The intrusions are shown on the Survey Sheet 338 as a few relatively large outcrops which in fact largely correspond to boulder belts and not to the true outcrop of the intrusions. About one hundred sills have been mapped on the six-inch scale. Most of these occur within the aureole of the granite. Their boundaries can only be mapped with certainty between Cox Tor and Smeardon Down where they are within the aureole and have an appreciable inclination (Fig. 6). Elsewhere an attempt has been made on the map to show the sill form of these intrusions.

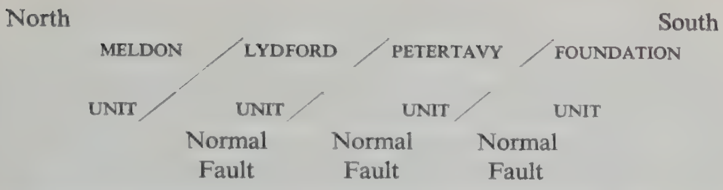
The sills vary in thickness from a matter of inches to 200–300 feet, as in Wilminstone Quarry (490755). The lenticular form of the sills is best seen in Pitts Cleave Quarry (501762) (Fig. 4). Many of the sills have irregular jointing, some however show well-developed columnar jointing. The sill rocks are mostly fine- to medium-grained, greenish in colour, with rare phenocrysts, although the margins are sometimes porphyritic. Vesicular margins are often seen. Most of the sills are of oligoclase-dolerite with generally fresh augite, altered felspars, tremolite, chlorite, ilmenite, apatite and epidote. Other rock types are recognised, the whole suite exhibiting a differentiation sequence (Butcher, 1958).

Spilitic lavas occur near the top of the Tavistock Calcareous Group in and near Tavistock, and are identified as being vesicular throughout their entire thickness. The large outcrop shown on the map just east of the town may be composed of a number of flows interbedded with sediments.

4. THE STRUCTURE

The main southern boundary of the great Culm Measures trough of Devon and north Cornwall is well defined by the appearance to the south of a monotonous series of Upper Devonian Purple and Green Slates. This junction can be traced from near Boscastle on the coast east-south-eastwards to Launceston and thence through Tavistock to the western margin of the Dartmoor granite. But there is, as De la Beche recognised in 1839, a line of (Lower Culm Measures) limestone quarries, shown in Fig. 1, extending from Launceston which curves round the northern verge of Dartmoor.

The geological structure is complex within the triangular area between this northern line of limestone quarries and the Culm Measures boundary to the south. We have found along the granite margin three lithological series, the Transition Series and the Lower and Upper Culm Measures, repeated in different but related structural settings. The structures have been separated into four major units:



The Foundation Unit extends far to the south of the area mapped, and comprises Upper Devonian Slates which dip at low angles to the north and to the south.

The Petertavy Unit is within the Culm Measures, with the exception of one small faulted Famennian inlier at Marytavy. It is characterised by a recumbent zig-zag fold pattern. On the south side of the extensive Lower Culm outcrop in Tavistock a narrow band of northerly dipping inverted Upper Culm greywackes lies above the Upper Devonian Slates of the Foundation Unit, but near the granite this order of superposition is locally reversed with the Upper Culm passing south beneath the Devonian. There is a repetition of dominantly inverted north-westerly dipping Upper Culm Measures in the northern part of the Petertavy Unit.

The Lydford Unit in this area is a narrow faulted complex of small-scale nearly isoclinal recumbent folds in the Transition Series with the north-westerly dipping Watervale Calcareous Group on the southern side of the unit.

The Meldon Unit, in contrast to the other units, has a well-defined structure. An inlier of Lower Culm Measures has a major zig-zag anticlinal structure overturned to the south towards the granite. Its outcrop appears on the map (Fig. 14) as a narrow band swinging round the northern margin of the granite from which it is separated by an overturned major syncline in the Upper Culm Measures. The southern low-dipping limb of this syncline is faulted down against the Lydford Unit on the western margin of the granite. The Transition Series occurs as a narrow faulted anticlinal inlier within the Lower Culm Measures.

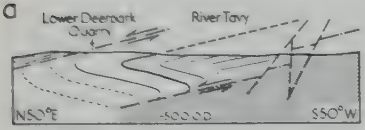
(a) The Foundation Unit

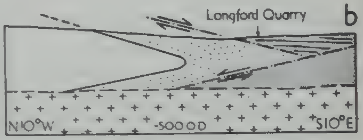
Since the slates of this unit crop out over a north–south distance of twelve miles between Tavistock and Plymouth there is most probably repetition of the strata by folding and faulting. The generally flat slaty cleavage probably approximates to the bedding in most instances, and although no folding is seen in our area it is suspected that there is a fold pattern of recumbent isoclinal folds.

A widespread development of fine north–south lineation is due to the intersection with the flat foliation of close-set cleavage planes which dip steeply to the east and to the west. A gentle east–west rucking also occurs in these slates.

(b) The Petertavy Unit

The southern boundary of the unit is complicated by considerable post-granite faulting (Fig. 14, and Fig. 2 a). The northern limit of the unit is taken as the northern boundary of the Black Down Group of the Upper Culm Measures, since the nearby occurrence of proven Famennian (the Manor Hotel, South and North Brentor Beds) suggests that this is a major fault junction. Within the unit the junction between the Lower and Upper Culm Measures near Marytavy must also be a major fault because of the presence of the Famennian inlier and the cutting out of the Calcareous Group near the granite (Fig. 14).





▭ Upper Culm ▭ Calcareous Group ▭ Devonian ⊞ Granite Scale 0 ——— 1000 Feet

Fig. 2a. Section 1, through the southern margin of the Petertavy Unit in Tavistock
Fig. 2b. Section 2, through the southern margin of the Petertavy Unit near the granite margin

Over most of the outcrop the bedding has a westerly dip component off the granite, whilst in the extreme south-western corner of the area the dips have an easterly component. The granite surface along the margin with the country rocks dips westerly at 5° to 10°. There is a large embayment in the granite margin, with a small granite inlier in the Youldon Brook (546801), and small patches of the country rocks on the granite near Standon Hill and Hare Tor. The embayment is due to a shallow 'valley' in the granite surface which plunges at 5° slightly north of west.

(*i*) *The Southern Upper Culm Structures.* It seems clear from the evidence of graded-bedding and cross-lamination found in the River Tavy section in Tavistock, that most of this greywacke group is inverted, passing north-eastwards beneath the Lower Culm Measures (Fig. 2 a). The Upper Culm is here separated from the Devonian by an east–west post-granite fault, but because of the northerly dips in both series the inverted Upper Culm is presumed to lie above the Devonian. The bedding within the Upper Culm dips at angles of up to 45° in directions varying from slightly west of north, round through east, to slightly west of south, this change in dip direction generally taking place from south-west to north-east along the section.

One isoclinal fold has been identified in the cross-laminated beds, described on p. 61, north of the footbridge (479741); some twelve feet of beds, proved to be the right way up, dip at 25° north-east and lie between inverted beds which above dip at 35° to N. 10° E. and below dip at 20° to

N. 25°E. The calculated fold axes plunge at 25° to N. 60°E. and 20° to N. 15°E. respectively. This single example suggests that other close folds are probably present in this group. Both in this river section, and in the railway cutting 500 yards to the north-west, the bedding planes of the greywackes are frequently polished, and stepped north–south slickensides indicate normal faulting movements on the northerly dipping bedding. The interbedded shales have the same fine north–south lineation that is so conspicuous in the Foundation Unit.

To the east the Upper Culm is poorly exposed, but near Longford (521747) southerly dips are recorded, and it seems significant that the foliation in the Devonian slates also has a southerly dip. The junction is therefore interpreted as a major fault dipping to the south, and it is suggested that here the Devonian lies above the Upper Culm (Fig. 2 b).

(*ii*) *The Lower Culm Structures*. The extensive Lower Culm outcrop is in part due to the low-dipping bedding, near horizontal strata being quite frequently developed. There are both northerly and southerly dips in the southern part of the outcrop which on the map (Fig. 14) give an impression of gentle east–west folding.

A sill, 200 feet thick, is exposed in the hinge of a recumbent fold (Fig. 3) in Wilminstone Quarry (490755) (Fig. 14). The bedding planes in the shales exposed in the tightly folded core in the northern face of the main quarry are polished, rucked and occasionally slickensided. The core of the fold is crossed by a sub-horizontal shear cleavage which can be traced into the sill. This cleavage can be studied in the better exposed upper limb of the fold (Fig. 3) where it displaces the lamination in the shales, and the offsets indicate a general northerly movement of upper relative to lower masses. A poor cross-lamination found in the upper limb suggests that this limb, which dips at 30° to S. 5° E., is the right way up. The dip steepens gradually to vertical at the hinge, where the bedding turns sharply to dip at 30° to N. 55° W. It is obvious that there is a considerable plunge to the fold axis here, and this is calculated to be 14° to S. 60° W. and is down the dip of the axial plane. The line of section in Fig. 3 is drawn at right angles to the trend of the fold axis.

A small recently reopened working to the north of the main quarry (Fig. 14) provides, at a higher level and to the east of the above locality, another exposure of this tight fold core. Here the fold axis has only a very slight plunge again towards S. 60° W.

At the present time the sill is well exposed in the west face of the main quarry (Fig. 14), where it is overlain at the top of the face by shales which dip at 65° towards S. 5°E. Conspicuous columnar jointing has a fan arrangement, the columns dipping at 20° towards N. 15° W. at the quarry top whilst in the quarry floor 110 feet below they are nearly horizontal. The columns are slightly bent and are crossed by cleavage planes dipping at 30° to S. 10° E. The axial plane of the fold must here be some fifty feet below the quarry floor. Vertical north-north-west to south-south-east joints perpendicular to the fold axis are well developed in both the sill and the sediments. The concordant relation of the sill to the sediments, and the deformation structures seen in the sill itself, supported by thin section observation of shearing and intense alteration, are taken to indicate that the sill was folded with the sediments.

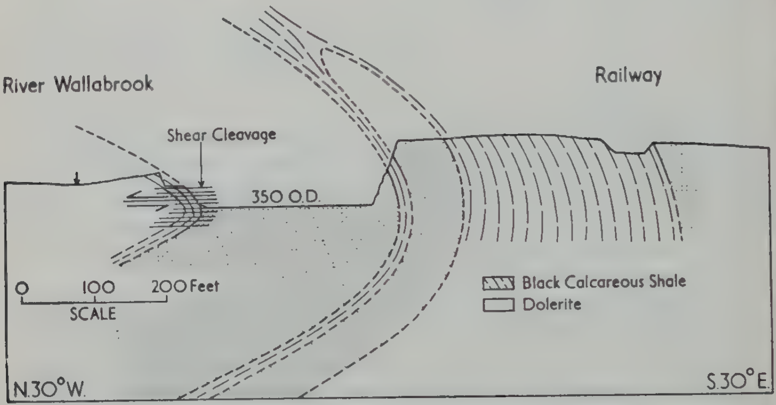


Fig. 3. Section 3, through the recumbent fold in Wilminstone Quarry

The nearby Pitts Cleave Quarry (501762) provides an exposure through three main lenticular sills interbedded with hard black shales (Fig. 4). The lower sills are thirty feet thick, whilst the upper sill is at least fifty feet thick and there are other smaller masses. The main face of the quarry trends nearly north–south (Fig. 14) and is 1000 feet long; at the southern end of the face the sills and sediments are nearly horizontal, the dip increasing northwards until in the extreme northern end of the quarry, in an inaccessible exposure, the sediments become vertical. Columnar jointing is developed at right angles to the bedding only in the upper sill. The bedding dips at 20° in a west-north-westerly direction in lower levels in the southern part of the quarry. The change in attitude in the main face suggests the nearby presence of a fold hinge in the northern end of the quarry. Hence it seems as though this quarry may expose a single limb of a recumbent fold tilted to the west. The length of this limb would therefore be at least 1000 feet.

Recumbent folds, but on a very much smaller scale, are present in the laminated calc-flintas exposed in an old quarry on Smeardon Down (522779). Here, two attitudes of bedding can be made out, an upper limb dipping at 10° to S. 20° E. and a lower limb dipping at 20° to N. 25° W. with

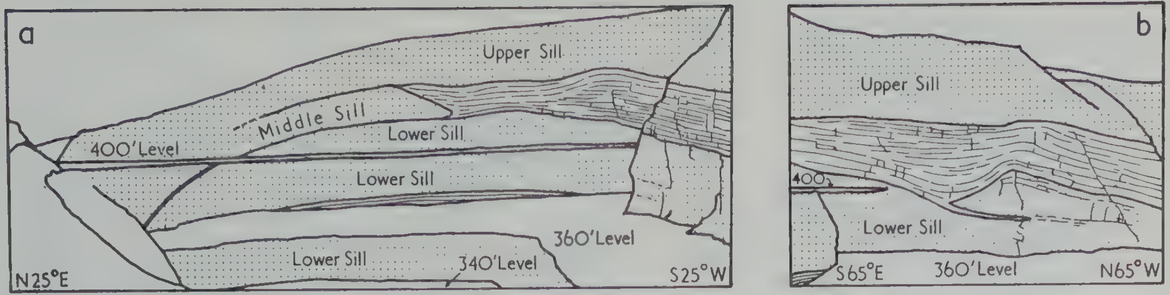


Fig. 4. The relation of the sills to the sediments in Pitts Cleave Quarry. Views of (a) the main face, *c.* 700 feet in length, and (b) the southern face, *c.* 250 feet in length

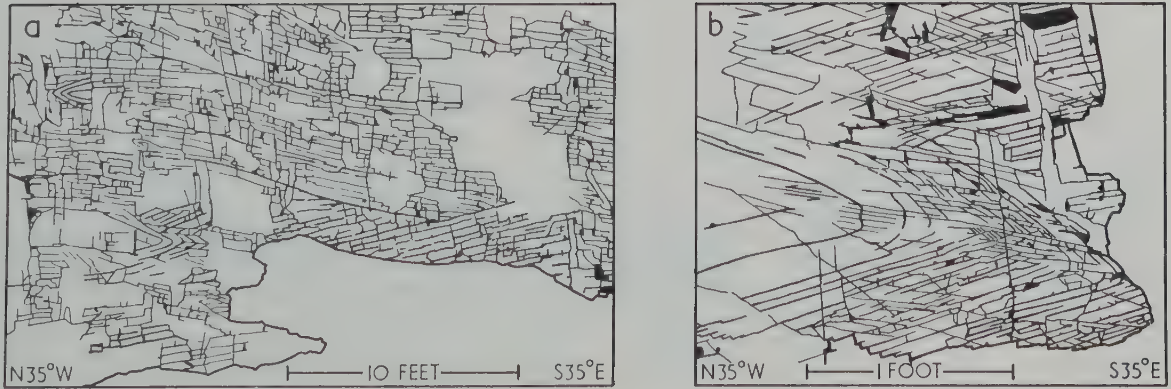


Fig. 5. Small-scale recumbent folds in calc-flintas exposed in a disused quarry on Smeardon Down. (b) The details of small folds crossed by shear cleavage seen in (a)

a smaller recumbent angular fold superimposed on the lower limb (Fig. 5). Sub-horizontal shear cleavage, parallel to the axial planes, displaces the bedding with upper masses moving north relative to the lower masses. The horizontal fold axes trend in a direction S. 70° W. It would appear that these are small folds in the limbs of larger recumbent folds, since below and above this exposure there are sills which are concordant with the northerly dipping bedding.

Only one locality is known in the Lower Culm where the 'way up' can be established with certainty. In Lower Deerpark Quarry (483743) in Tavistock about twenty-five feet of horizontal black limestones are overlain by shales and hard siliceous beds. North–south slickensides are seen on the bedding planes. In the northern end of the quarry a slight northerly dip increases, until fifty feet to the north it reaches 50°. These steeper beds can be proved to be inverted from a nine-inches thick graded tuff bed which they contain. This suggests therefore a northerly dipping inverted limb of a recumbent fold (Fig. 2 a).

All these observations, taken together, suggest that there is a fold pattern in the Lower Culm of recumbent zig-zag folds with normal southerly dipping limbs and inverted northerly dipping limbs, and that these folds vary in size. The thicker sills lie in the limbs of the larger-scale folds where the length of the limbs must be at least 1000 feet, and small-scale folds of the same pattern occur in the sediments within these long limbs. This could be readily explained as due to the competency of the sills during deformation, the sediments being relatively incompetent. It is an observable fact, especially within the aureole, that the margins of the sills are extensively sheared on planes approximating to the bedding of the sediments. These sheared margins contrast with the massive interiors of the sills. The sills appear to be much more sheared in the ground between Marytavy and the granite than they are in the southern part of the Lower Culm outcrop.

(*iii*) *The Famennian Inlier*. This inlier at Marytavy is poorly exposed, and the boundaries cannot be determined. The slates have a low westerly dip, and on the bedding is to be seen the fine north–south lineation first observed in the Foundation Unit.

(*iv*) *The Northern Upper Culm Structures*. The Upper Culm on Black Down is poorly exposed. The best section is that seen on the southern side in the stream which flows down through Wheal Betsy. This is largely a strike section in generally inverted beds which dip steeply in a north-westerly direction. Near the head of the stream where the mine leat is led in (521817), a nearly recumbent zig-zag fold is exposed (Fig. 6); the upper inverted beds dip at 45° in the direction N. 15° W., a middle normal limb about ten feet in length dips at 10° to S. 20° E., and the lower inverted beds dip at 30° to N. 15° W. The axial planes thus dip at 10°–20° to N. 15° W.

Though it would be rash to deduce the fold pattern from this one example there is no doubt that inverted beds predominate in this stream section.

Near the northern boundary of the Upper Culm there are poor exposures in the stream leading down to the River Lyd which show both flat and steep inverted bedding, dipping north-westerly, with an occasional steep south-easterly dip in normal strata (Fig. 7). This evidence must be interpreted as indicating steep flexures in otherwise flat inverted beds with occasional overturning of the steep limbs to give beds the right way up; in fact a small dip section by an old adit (513831) shows this pattern.

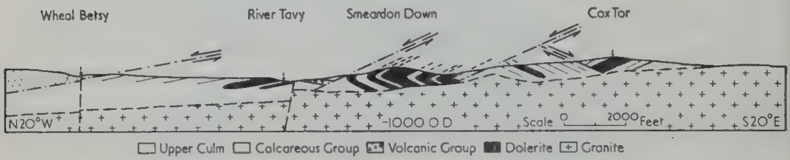


Fig. 6. Section 4, through the Petertavy Unit from Wheal Betsy through Cox Tor to the granite

(c) The Lydford Unit

There is no suggestion of major structures within the Transition Series in this unit. An exception is the possible repetition of the northern altered calcareous siltstones on the southern side of the inlier in the railway cutting on the Launceston line (p. 59). The absence of thick competent beds in this River Lyd Group has determined the small-scale recumbent fold pattern distinctive of this group.

(*i*) *The Watervale Group Structure*. The bedding in this group dips at between 30° and 40° north-westerly, and no folds have been seen in the poorly exposed ground.

(*ii*) *The River Lyd Group Structures*. The small-scale structures in this group are best seen within the aureole in the valley of the River Lyd below High Down (Fig. 14). Here weathering has picked out details of the original lamination which has been emphasised by the contact metamorphism. Folds, even when distorted by shear cleavage, plunge at 20° to the west off the granite. The two bedding attitudes in the folds, typically 35° north-westerly and 10° to 30° nearly due west, have controlled the development of a later shear cleavage. It can be demonstrated that normal faulting movements are associated with the steeper cleavage, and that reverse faulting occurs along the other flatter cleavage. At particular localities one set is developed to the almost complete exclusion of the other. Below High Down, for example, normal faulting on the cleavage predominates, and the effect of this is to produce pronounced distortion of the lamination at the fold hinges. The fold limbs are then connected by nearly vertical zones of intense rucking.

Another type of structure is to be seen at Kitt's Mine (517846); monoclinal flexures occur in which beds dipping at 25° to 35° in a north-westerly direction are connected by steep rucked beds dipping more nearly west-north-west. These rucked beds are crossed by an intense shear cleavage, dipping at about 10° to east-south-east, on which reverse faulting movements have taken place. No folds are to be seen, but it is thought that the ruck zones represent fold limbs the attitudes of which have been completely changed by the reverse faulting associated with the shear cleavage.

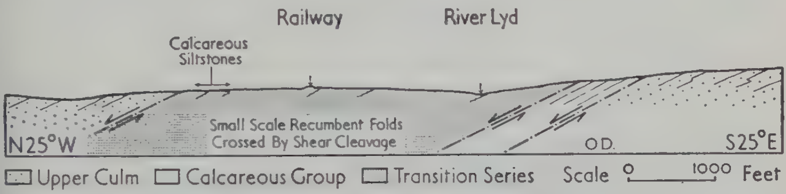


Fig. 7. Section 5, through the Lydford Unit

The bedding dip varies between 15° and 40° to the north-west in Lydford Gorge (Fig. 14), outside the limits of the aureole. The occasional juxtaposition, either laterally or vertically, of bedded masses having these extremes of dip suggests the presence of nearly recumbent folds. Such folds have been found, but are always distorted by shear cleavage. Vertical rucked beds, connecting flatter evenly dipping beds above and below, have also been found and, as at Kitt's Mine, the ruck zones are crossed by shear cleavage dipping at a low angle counter to the bedding.

(d) The Meldon Unit

The structures in the Meldon Unit are determined by zig-zag folding, with long straight limbs and sharply turned crests and troughs, which presents a pattern of folds overturned to the south. This fold form is broken by strike faults along the bedding; normal faults are parallel to the steep inverted bedding, and reverse faults have the attitude of the gently inclined bedding found in the normal limbs of the folds.

(*i*) *The Southern Upper Culm Structures.* The major syncline in the Upper Culm Measures next to the granite has smaller anticlinal rucks developed on both limbs. These can be seen on the steep inverted limb at the Torwood Mine (537891). On the Red-a-ven Brook at Meldon small folds on the southern gently inclined limb of the syncline have been flattened out by later reverse faulting along the low-dipping bedding. A major reverse fault is known to cut the steep limb of the same fold 150 yards beyond the southern boundary of the Lower Culm inlier (Fig. 9).

The axis of the major syncline must be approximately horizontal from Gooseford in the east to the Prewley Fault; beyond this point the southern limb of the fold diverges from the granite margin, and the syncline plunges at 5°–15° to the south-west. The granite surface follows a definite bedding horizon in the flat limb of the syncline. The surface dips at 15° to the north on the northern slopes of Cawsand Hill, where there is a local offset of the granite surface into the attitude of the adjacent steep bedding (Fig. 11). A contact is exposed on the East Okement River between the Upper Culm and a late fine-grained granite emplaced as a sheet into the coarser granite forming the local tor masses. This fine-grained granite is exposed for a considerable distance in the river bed, but ends abruptly against a joint plane dipping steeply to the south, counter to the bedding in the Upper Culm Measures. The attitude of granite dykes in the sediments is subject to the same joint plane control, and excellent examples are exposed on the Red-a-ven Brook and adjacent streams (Fig. 14).

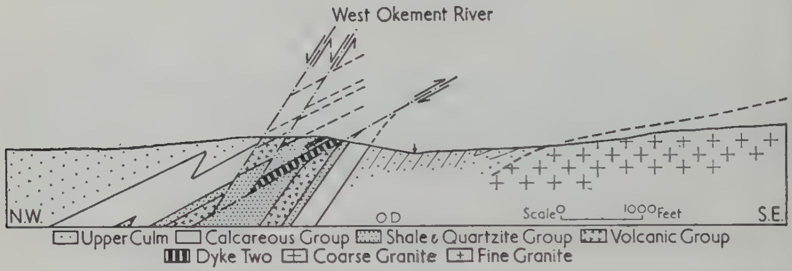


Fig. 8. Section 6, through the Meldon Unit along the south-west side of the Prewley Fault

(*ii*) *The Lower Culm and Transition Series Structures*. The structures change in nature along the strike of the Lower Culm Measures inlier. A single overturned anticline enters the area from the south-west; limestones have been worked at Sourton and Bridestowe in the low dipping Calcareous Group on the northern limb of this fold, whereas the same beds in the inverted steep southern limb are mineralised and have been mined at Wheal Fanny (522884) and Torwood Mine. The structure of the inlier along the line of the Prewley Fault, shown in Fig. 8, was confirmed in the excavations made for the Prewley Waterworks Tunnel (552907). Normal faults cut out the limestones in the normal limb of the fold, and a reverse fault which cuts the steep beds has been invaded by a thick sheet of Dyke Two facies. Tuffs in the inverted limb of the anticline exposed high up on Sourton Tors have been flattened by this reverse fault, which must be held responsible for an intensive development of low dipping shear cleavage in the lustrous grey shales exposed beneath the Volcanic Group in the railway cutting (533893) north of Lake Viaduct.

The steep limb of the anticline continues unchanged beyond the Prewley Fault to the Red-a-ven Brook, but on South Down a second major anticline arises on the northern limb of the fold. A well-defined central syncline in the Calcareous Group thus separates a northern from the southern anticline in this area and folds plunge from this point towards the West Okement River where the limestones have again been worked. Aplite dykes, emplaced along joints through tuffs and calc-flintas in the normal limb of this syncline, have been worked on both banks of the Red-a-ven Brook.

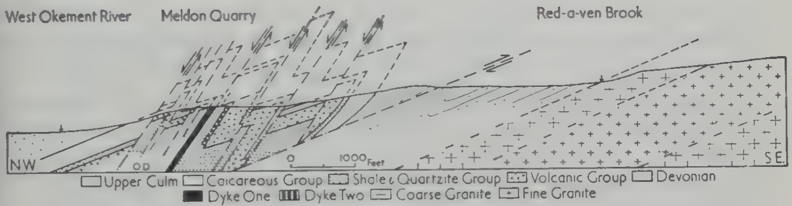


Fig. 9. Section 7, through the type area of the Meldon Unit from the Railway Quarry to the granite

On rising from the valley the plunge of the central syncline is reversed to south-west, and additional minor anticlinal rucks arise on the low-dipping limbs of both anticlines. These structures are illustrated in Fig. 9; the ruck on the normal limb of the southern anticline has been proved by excavation, but the northern anticline with the minor anticlinal ruck is fully exposed on the West Okement River and in the main working faces of the Railway Quarry. In the North Bay of this quarry the anticlinal ruck is repeatedly broken by steep hinged normal faults, and a reverse fault along low-dipping bedding can be traced into the adjoining South Bay where it cuts across steep beds in the inverted limb of the northern anticline. One intrusive sheet of Dyke One facies follows the steep bedding and has been traced eastwards almost to the East Okement River. Another sheet, of the contrasted Dyke Two facies, ends abruptly against the reverse fault mentioned above; it is emplaced along the bedding at the base of the Volcanic Group, and is exposed at the same horizon on both the East Okement and Taw Rivers but dies out before reaching the Sticklepath Fault.

The southern anticline is exposed on the Red-a-ven Brook, the steep limbs of both anticlines converge eastwards, and unite on Moor Brook. The resultant anticline on the East Okement River, Fig. 10, has a core of the Meldon Slate-with-Lenticles Group. Both here, and in the core of the

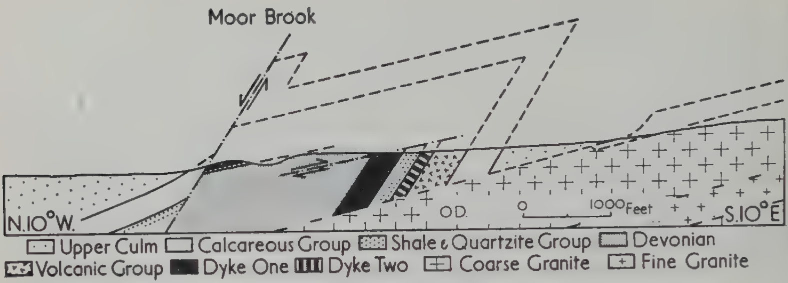


Fig. 10. Section 8, through the Meldon Unit on the East Okement River

northern anticline exposed in the Railway Quarry at Meldon, the characteristic minor structure of this group—small-scale nearly isoclinal folds—is well displayed.

The northern low-dipping limb of the East Okement anticline is broken by a normal fault which cuts out the Calcareous Group to the east of the river. But interest here is centred on two intrusive sheets of Dyke One facies; a dyke in the steep inverted limb of the fold is abruptly terminated on the west bank of the stream, and the shape of the outcrop suggests that the upper surface of the dyke is a low-dipping reverse fault plane. This dyke can be traced into the neighbouring valley of the Taw River where it becomes thinner and dies out before the Sticklepath Fault is reached. The other sheet is emplaced along the low-dipping bedding; it can be followed westwards in the same setting almost to the Railway Quarry at Meldon, and eastwards to Sticklepath. On rising from the deep valley of the East Okement to the higher ground around Belstone (619935) the two sheets coalesce to form a single anticlinal intrusion (Fig. 11).

The steep inverted limb of the anticline continues unchanged across the Sticklepath Fault, but the Volcanic Group becomes thinner and eventually dies out in the valley of the Taw. North-east of Belstone the Calcareous Group reappears at the northern margin of the anticline; the only exposure is on the main road at the entrance to the disused Devon County Council Quarry (638944) at Sticklepath where the beds are vertical and are

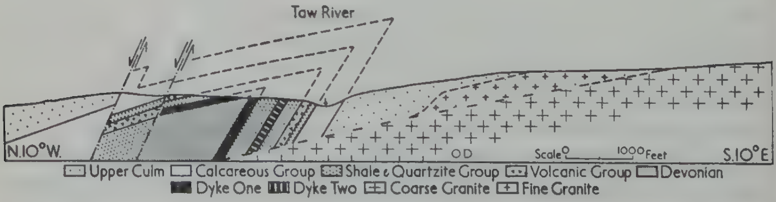


Fig. 11. Section 9, through the Meldon Unit to the west of the Sticklepath Fault

weathered to a rusty-brown rottenstone. The steep dip of the Calcareous Group is confirmed by Smyth's (1875) description of the underground workings in the neighbouring Belstone Consols Mine (632946). Collins (1912, pl. 2, fig. 3) has provided a cross-section through the mine, and Ormerod (1867) stated that the Dyke One sheet passes through the workings to the south of the mineralised zone. It is necessary to assume on the evidence of these underground details that the steeply dipping Calcareous Group is limited on both sides by normal faults along the bedding, as shown in Fig. 11, and that another anticline has arisen on the normal limb of the East Okement River anticline.

Movement along the Sticklepath Fault has displaced the Belstone Consols Mine outcrop of the Calcareous Group 5800 feet to the south-east, where the same beds have been worked in the Ramsley Mine. The structure to the east of the fault is illustrated in Fig. 12. The Volcanic Group reappears in steep beds at the northern margin of the inlier, and at Gooseford the inlier is, with this exception, entirely within beds of the Calcareous Group.

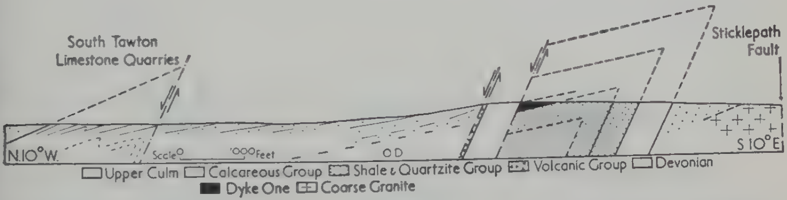


Fig. 12. Section 10, through the Lower Culm inliers on the eastern side of the Sticklepath Fault

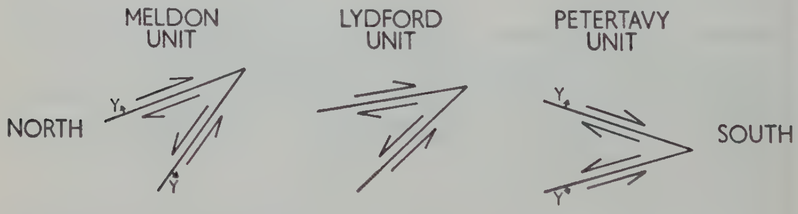
(*iii*) *The Northern Lower Culm Inliers*. The outcrop of the Calcareous Group at the South Tawton limestone quarries occupies a topographic hollow; exposures on the Taw River to the west along the strike are entirely within the sandstones and shales of the Upper Culm Measures. The limestones have a general northerly dip of from 10° to 25° interrupted by small overfolds. Flat beds in these folds are cut by a steep shear cleavage and by normal faults covered with slickensided calcite layers. The nature of the northern boundary cannot be determined; flat beds on the southern side are contorted, veined with calcite, and cut by steep normal faults suggesting that this boundary is a major normal fault (Fig. 12).

At the western end of the area there are shallow chert quarries on the south side of the main road leading to Bridestowe (536913). The limits of the chert outcrop have not been determined, but the trench for the water main from Prewley Waterworks revealed Upper Culm Measures in the valley of the Thrushel. Here, as at South Tawton, there is a small inlier beyond the northern limits of the main inlier of the Meldon Unit.

(*iv*) *The Northern Upper Culm Structures.* The absence of well-defined lithological groups in the Upper Culm Measures to the north of the Lower Culm inlier may mask structures comparable in scale to the syncline on the south side. There is, however, a wide band of low-dipping rocks in the valley of the East Okement south of Fatherford Viaduct (604948) but even here multiple overfolds are developed close to the junction with the Lower Culm. Overfolds, with limbs a few tens of feet long, broken by normal and reverse faults along the bedding, are exposed in the railway cuttings at Okehampton Station (588943) and in the Brickworks (594962) to the north of the town. At both localities there is a curious association of overfolds with groups of symmetrical folds in which the limbs are the right way up.

(e) Structural Interpretation

There is a change in the attitude of the folds within the three northern units as they are followed from south to north. This may be represented diagrammatically as follows:



The folds in the Lydford Unit close to the granite margin are intermediate in attitude between those found in the Petertavy and Meldon Units. This change in attitude appears to be due to the effect of the granite emplacement. The recumbent folds in the Petertavy Unit plunge westerly at 5° to 15°, sub-parallel to the dip of the granite surface. The granite surface on the northern margin dips northerly at steeper angles and is concordant with the normal limb of the major syncline in the Upper Culm Measures which now has a horizontal axis and a considerable northerly axial plane dip (Fig. 9). Where the granite margin changes direction south-east of Sourton Tors, a south-westerly plunge of 5° to 15° is imparted to the Upper Culm syncline. Folds close to the granite margin in the Lydford Unit have a westerly plunge of up to 20°, but this plunge decreases to the west until the fold axes are nearly horizontal outside the aureole in Lydford Gorge.

This variation in the structural pattern suggests that the folds were originally recumbent over the whole area, and that the emplacement of the granite lifted up the folds. As a result the characteristic structure of the Meldon Unit, namely folds overturned to the south, is really the result of the tilting to the north of recumbent folds. There has been north-westerly tilting of the folds in both the Lydford Unit and at the south-western end of the Meldon Unit, whilst in the Petertavy Unit there has been simple tilting to the west.

Folds in the Meldon Unit are broken by strike faults along the bedding, and these are low-dipping reverse faults and steeply dipping normal faults as seen in their present attitude. These strike faults, before the granite emplacement, would have been normal faults dipping at low angles to the north and to the south, cutting the original recumbent folds. These normal faults represent a continuation of the bedding plane slip movements necessary for the generation of the zig-zag folds. The structural pattern of recumbent zig-zag folds combined with the later normal faulting indicates a continuous north–south horizontal elongation of the folded mass (Fig. 13).

A remarkable feature of the area is the repeated juxtaposition of the three lithological series to the north of the Upper Devonian Slates, and an attempt has been made to explain this in Fig. 13. In this diagram it is assumed that we are dealing with a vertical pile of recumbent folds in which, on the evidence of sedimentary structures, the Lower Culm Measures are followed to the south by the Upper Culm, and to the north by the Devonian. Recumbent anticlines close to the south.

The horizontal elongation of this pile initiated during the folding phase of deformation was continued with the development of the normal fault system. Simultaneous and equal normal faulting movements to both the north and south along the bedding planes are insufficient to explain the present disposition of the lithological series within the three structural units. Fault-slip to the north, on the interpretation presented in Fig. 13, has to be almost double the amount of slip to the south. It is suggested that the additional slip on the northerly dipping faults is closely related to the mechanism of emplacement of the Dartmoor granite; these faults were reactivated during the emplacement, and permitted at least some of the additional crustal stretching necessary to make room for the granite. The structural units are thus bounded by major normal faults dipping at low angles to the north.

These northerly dipping normal faults are most likely hinged, with a focal point somewhere east of Launceston, the fault-slip increasing from this point eastwards towards the granite margin. This would explain the curious divergence between Launceston and the granite margin of the northern line of Lower Culm limestone quarries from the southern boundary of the main outcrop of the Culm Measures (Fig. 1 and p. 64).

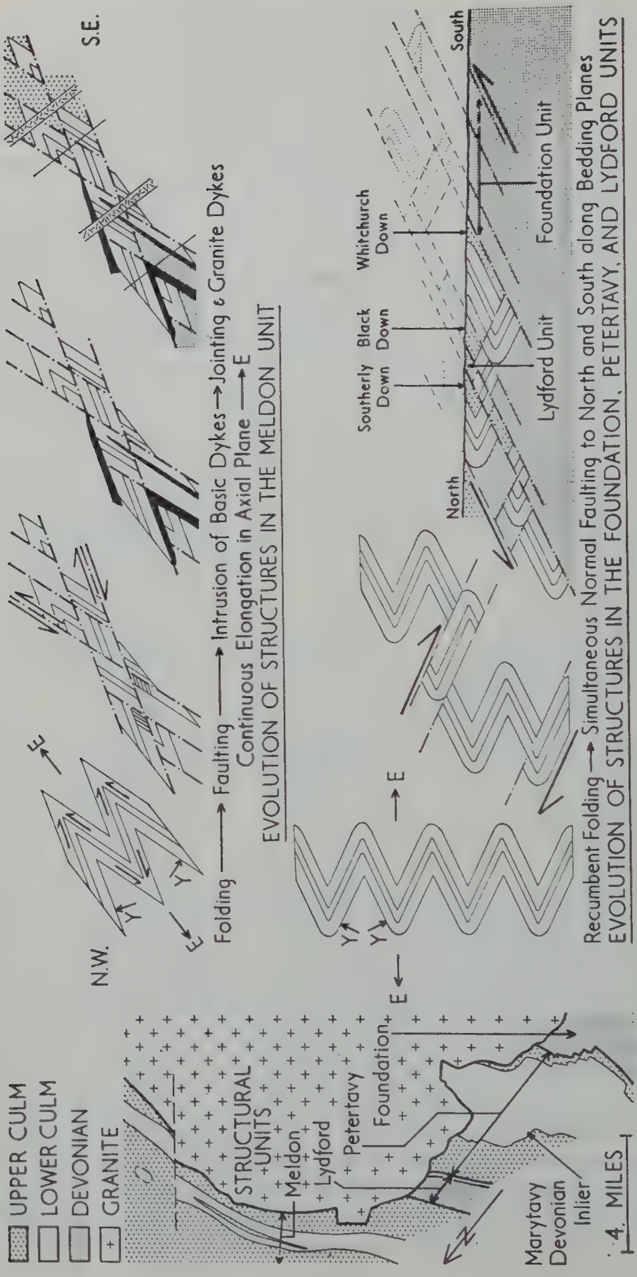

UPPER CULM
LOWER CULM
DEVONIAN
GRANITE
STRUCTURAL UNITS
Meldon
Lydford
Petertavy
Foundation
Marytavy Devonian Inlier
4 MILES
N.W.
S.E.
E
Y
Y
E
Folding → Faulting → Intrusion of Basic Dykes → Jointing & Granite Dykes
Continuous Elongation in Axial Plane → E
EVOLUTION OF STRUCTURES IN THE MELDON UNIT
E
Y
Y
→ E
North
Southerly Down
Black Down
Whitchurch Down
South
Lydford Unit
Foundation Unit
Recumbent Folding → Simultaneous Normal Faulting to North and South along Bedding Planes
EVOLUTION OF STRUCTURES IN THE FOUNDATION, PETERTAVY, AND LYDFORD UNITS

Fig. 13. The structural interpretation of the area

(f) The Breccia-Fault System

An extensive system of breccia-faults cuts both the country rocks and the granite (Fig. 14). Some of these have been mapped, and additional information has been obtained from mine plans and from Dines (1956). Many more faults undoubtedly exist than are shown. East–west breccia-faults occur in the Petertavy district, the most important being the Cudlipptown Fault. These are cut by the later, and more important, 'cross-courses', faults which trend between north-west to south-east and north to south. The more northerly trending of these faults arise as offshoots from the more north-westerly trending faults.

Data on these faults are limited. In Tavistock they trend N. 30° W. and downthrow to the north-east with north-easterly dips of 55° as revealed by the operations of Wheal Crelake (478737). An apparent dextral displacement of earlier structures is noted. Farther east, the more northerly trending Devon Burra Burra Faults dip steeply west with an apparent sinistral offset of earlier structures. The main fault here has nearly north–south offshoots. At Marytavy the faults are known in some detail; Wheal Friendship Fault trends N. 20° W. and dips 50° in a westerly direction with a westerly downthrow of 200 feet, the movement being completely dip-slip. Northerly trending steep westerly dipping faults branch off this main fault; Brenton's Fault is a sinistral tear fault with a throw of ten feet and strike-slip of fifty feet in Wheal Friendship.

The next fault for which data are available is the Prewley Fault which trends N. 35° W. and is marked in the granite by a prominent valley through which the West Okement River flows. It is essentially a vertical fault with a north-easterly downthrow of 550 feet, the movement being almost completely dip-slip. Northerly trending shatter belts off this fault were located in the Prewley Waterworks Tunnel. Two main breccia-fault zones, of similar trend to the Prewley Fault, were located in the Railway Quarry at Meldon. One, 165 feet wide, is exposed in the quarry face but is not brecciated throughout. There is a north-easterly downthrow of at least seventy feet, the movement again being almost completely dip-slip.

The biggest fault in the area is the Sticklepath Fault which occupies a zone 250 yards wide. It is a dextral tear fault trending N. 40° W. which offsets the main Lower Culm inlier a total distance of 6500 feet. Belstone Consols Mine is situated on north–south offshoots from the main fault. Smyth (1875) states that 'the entire lode is heaved by a cross-course . . . a distance of nine fathoms south in going west; and a succession of considerable dislocations in the same direction occur still farther west'.

It is worth noting that the continuation of the Sticklepath Fault zone to the north-west passes through the displaced outcrops of the Permian to the north of Okehampton (Fig. 1), where the displacement is again dextral and of similar amount. The fault zone continues south-eastwards as the Lustleigh Fault (Blyth, 1957).

5. CONTACT METAMORPHISM AND METASOMATISM BY THE GRANITE

Mineralogical changes induced in the country rocks after the emplacement of the Dartmoor granites are closely related to the sequence of tectonic events described above. The approximate outer limit of the contact metamorphic aureole is shown on the map (Fig. 14); the thickness of the aureole is about 1500 feet. Fracturing of the granite and its roof rocks during the ruptural phase of deformation heralded the release of reactive emanations from the cooling granite. Impressive metasomatic changes resulted; these took place along joints and other structural planes, and clearly have been superimposed on the earlier effects of contact metamorphism. A final phase of mineralisation resulted in the formation of east–west tin–copper lodes, with later deposition of lead mainly restricted to the north–south breccia-fault branches.

(a) The Sediments

(*i*) *The Whitchurch Green Slates*. These become spotted slates within the aureole, the spots developing into cordierite which is rarely found fresh but is replaced by chlorite, and is set in a matrix of colourless mica, quartz and iron ore.

(*ii*) *The Transition Series*. The Meldon and River Lyd Slate-with-Lenticles Groups are found within the aureole where the main change is the development of biotite in the shales. Silty beds in the River Lyd Group, close to the granite, recrystallise to coarse-grained quartz with muscovite. Red-brown garnets occur in some lenticles under High Down.

The chief feature of petrological interest in this series is the development, at horizons in the Meldon and River Lyd Groups, of brown and green banded rocks which simulate true calc-flintas. These are best seen on the northern side of the outcrop of the River Lyd Group. The brown bands are biotite-rich shale laminae, whilst the green bands comprise altered calcareous siltstone in which the original calcite cement has been replaced by a green hornblende (see pages 58 and 60).

(*iii*) *The Shale-and-Quartzite Group of the Lower Culm*. Contact metamorphism of this semi-pelitic group has resulted in the formation of biotite, chiastolite and cordierite in rocks of suitable composition. The black pigment may be cleared at this stage, but this change is usually associated with later fissure metasomatism. Several types of fissure reactions have been recognised. Fine-grained biotite may be formed at the expense of chlorite and muscovite in the reaction selvages along biotite,

biotite-quartz and quartz veins. The width of the reaction zone is dependent upon the nature of individual laminae, and is greatest in those of pelitic composition. This change may be followed in the same fissure by the formation of amphibole-quartz-sulphide veins with the development of an inner zone in which biotite is replaced by a green hornblende. Introduction at this stage of boron in sufficient quantity may result in complete tourmalinisation of the rock.

(*iv*) *The Calcareous Group of the Lower Culm*. There are three rock types to consider: impure limestone, black calcareous shale and black radiolarian chert.

The formation of marbles from the limestones does not appear to have been controlled by jointing, and on this account is considered to be a product of contact metamorphism. The black pigment is discharged, and wollastonite porphyroblasts are developed in the more siliceous limestones.

Biotite may arise in black shales of appropriate composition, and the presence of porphyroblasts of axinite serves to distinguish the calcareous shales of this group from the tourmaline-bearing shales of the Shale-and-Quartzite Group (see p. 60).

Contact-metamorphic effects are not readily determinable in the cherts; some silicification of the cherts appears to be later than the faulting phase of deformation as some radiolarian casts are deformed by shear cleavage. Early metasomatism removed the black pigment of the cherts along closely spaced joints and along the bedding planes with the formation of a black and white calc-flinta. Reactivity at this stage varied from lamina to lamina, and in some the pigment is completely cleared and the rock becomes a fine-grained aggregate of quartz-calcite-enstatite-scapolite. Thin veins along joints carry the same assemblage with a slightly coarser grain size.

Superimposed on these early changes is a great development of coarse-grained calc-silicate hornfelses associated with the introduction of sulphides and boron. Kernels of unaltered chert with white calc-flinta selvages remain as a reminder of their parentage within coarse-grained aggregates of grossularite, idocrase, diopside and wollastonite. Streams of unaltered grains from the calc-flinta are included within garnet and other minerals.

These changes may be studied conveniently at the northern end of the Railway Quarry at Meldon; here normal faulting in flat beds has brought the Calcareous Group down against the Volcanic Group. These faults offered major channels for the passage of metasomatising fluids thus localising the formation of the coarse calc-silicate hornfelses from the calc-flintas, and producing in the footwall tuffs and shales an exotic deposit of quartz-green hornblende-axinite-datolite.

The influence of the calc-flintas on metasomatic activity in adjacent rocks is well illustrated in the Meldon Aplite Quarries (567920) on both banks of the Red-a-ven Brook. Aplite is altered along joints to quartz-albite-fluorite-axinite-datolite veins up to two feet thick, and bavenite has been found in this setting. Vein reactions in the tuffs lying beneath the calc-flintas lead, through stages involving early removal of biotite, to the formation of grossularite-green hornblende-axinite rocks in which sulphides may be present. In these rocks the initial joint plane control of the metasomatism may no longer be apparent.

Smyth (1875) described the Calcareous Group in Belstone Consols Mine as 'an alternation of garnet rock and dark siliceous slates' in which there were three bedded lodes of greenish-brown grossularite. The lodes, with thin bands of green hornblende and axinite, are 'speckled throughout . . . with pyrites, mispickel, and black and grey copper ores'. Similar rock types are to be found in other mine dumps throughout the area. Material from the dumps of the disused mine on the Red-a-ven Brook, close to the junction of the Calcareous Group with the Upper Culm Measures, clearly demonstrates, however, that the cherts already altered to calc-silicate rocks were exposed to a localised final phase involving iron metasomatism. Pyrrhotite, with subordinate amounts of arsenopyrite and sphalerite, is intergrown with grossularite. The garnet may have an outer iron-rich shell, and is intergrown with a ferriferous wollastonite and hedenbergite.

There is a restricted occurrence of rhodonite with rhodocrosite and bustamite in the basal bed of the Calcareous Group within the steep limb of the central syncline exposed at the southern end of the Railway Quarry.

(*v*) *The Upper Culm Measures*. These are represented close to the granite by tough hornfelses in which it is difficult to separate original arenaceous beds from shales. The shales develop biotite and cordierite and occasionally andalusite, as recorded by Mennell (1915), north-west of Brat Tor. The arenaceous beds recrystallise but their detrital origin can still be recognised close to the granite. In the Whitchurch Down greywackes the carbonaceous matter is expelled.

(*vi*) *The Pyroclastic Deposits*. Tuffs are chloritic outside the contact metamorphic aureole of the granite; within it biotite, cordierite, anthophyllite, cummingtonite and a manganiferous garnet may be developed. Some at least of these minerals may be of later metasomatic origin; garnet has been found in a reaction selvage to biotite veins in shales interbedded with the tuffs, and in some cases anthophyllite and cummingtonite, associated with a coarse-grained development of cordierite, appear to be related to veins crossing the tuffs. The unusual calc-silicate hornfelses found in these rocks in the aplite quarry and elsewhere have been described earlier, but even here the final stage of more or less complete tourmalinisation is well represented.

(b) The Igneous Rocks

(*i*) *The Meldon District*. The metamorphic history of the two dykes exposed in the Railway Quarry at Meldon has an important bearing on the time relationships between the sequence of tectonic events in the sediments and the emplacement of the Dartmoor granite.

The original pyroxene of the ophitic albite-dolerite Dyke One facies has changed to green hornblende, which is in turn replaced by biotite. These changes have been seen as successive reaction rims around pyroxene nuclei, but may also occur as completed reactions. The resulting rock types, at varying stages of contact alteration, have suffered the same metasomatic changes as the associated sediments and these too are controlled by joints formed after contact metamorphism. Green hornblende-albite-sulphide veins have white selvages in which biotite has changed to green hornblende; later formation of tourmaline enhances these metasomatic effects.

A similar sequence of changes is to be seen in the porphyritic albite-biotite rock of Dyke Two facies. Contact metamorphism to the biotite stage is virtually complete; the earliest change of pyroxene to amphibole has been found in a similar rock type from Sourton Tors, and the next stage is preserved in small ovoid patches in the biotite-rich Meldon dyke. Fissure reactions continued after the formation of tourmaline-green hornblende-sulphide veins. Quartz veins, with abundant pyrrhotite, pyrite, chalcopyrite and other sulphides in smaller amounts, cut the earlier tourmaline veins and frequently have selvages of coarse-grained biotite which is partly altered to chlorite. Late tourmaline veins also have selvages in which the change biotite to chlorite has also been observed.

(ii) The Petertavy District. Here the full sequence of contact-metamorphic changes can be followed from outside the aureole to the granite margin. The first change in the dolerites is the replacement of tremolite by a green hornblende. Then augite is replaced by green hornblende and the rocks acquire a coarser grain. Chlorite is replaced by biotite and epidote disappears. Nearer to the granite the green hornblende is itself replaced by biotite which also develops generally in the rock. The felspar must be stable as it is the last original mineral to undergo significant change. Recrystallisation of the felspar laths to a mosaic results in the formation of an extremely tough hornfels. Relics of the original igneous textures are usually preserved; a blastophitic texture is the most common. A feature of the sills in both groups of the Lower Culm is the development of biotite-rich margins. Spessartite garnets occur in one small biotite-rich intrusion on the River Tavy below Hill Bridge.

Green hornblende veins are ubiquitous, occurring in both sills and sediments, and clearly have a metasomatic origin. Thin sills, and the margins of thicker sills in the Shale-and-Quartzite Group, show the replacement of the contact-metamorphic green hornblende by anthophyllite. This change proceeds to the final production of an anthophyllite-pleonaste-biotite-iron ore assemblage which may also include cordierite. The reactions involved are therefore similar to those described by Tilley (1935) from the aureole of the Land's End granite.

The tors of contact-altered dolerite frequently exhibit north–south and east–west joint sets, the faces of which are often coated with tourmaline rosettes. In the contact-altered sills east-south-east of Petertavy itself an intense bleaching occurs with which tourmaline is sparsely associated. Veins and patches of completely white rock, in which diopside is conspicuous, contrast with the adjacent green metadolerite.

(c) The Mineralisation of Breccia-Faults

The onset of breccia-faulting as the final phase of deformation coincided with the late hydrothermal stage in the cooling history of the granite. This is clearly shown on the Sticklepath Fault at Ramsley Mine where dolerite-breccia is grouted with quartz, calcite, chabazite and natrolite. Smashed calc-flintas on the mine dumps are cemented together by calcite, and heulandite occurs on the surfaces of the fragments.

In the Railway Quarry at Meldon heulandite-calcite veins have been found in open joints crossing both calc-flintas and the coarse grossularite hornfelses. Vughs in tourmaline-green hornblende veins cutting basic dykes in the same quarry are lined with apophyllite, stilbite and prehnite. Joint planes in limestones from the mine on the Red-a-ven Brook and from the limestone quarry on the West Okement River are coated with apophyllite.

Corroborative evidence of the time of brecciation is to be found from the granite itself. Loose blocks of reddened granite have been found at a number of places which are cut across by numerous parallel black tourmaline veins. The same rock type has been found brecciated and cemented by quartz.

There are east–west lodes as well as mineralised east–west breccia-faults in the Petertavy district. The main minerals developed in these are cassiterite with some scheelite, and arsenopyrite, chalcopyrite, pyrrhotite, pyrite, sphalerite and specularite in a gangue of quartz, chlorite and tourmaline. The cross-courses carry argentiferous galena, siderite, sphalerite and some pyrite and chalcopyrite.

6. CONCLUSIONS

The green slates found in the Transition Series are reminiscent in their colour of the Upper Devonian Slates to the south of Tavistock. This series also contains coarse black siltstones and shales, whilst the Shale-and-Quartzite Group of the Lower Culm Measures originally consisted of very fine siltstones and shales. Thus the Transition Series, taken as a whole, is gradational in colour and lithology between the Upper Devonian Slates and the Lower Culm Measures, and is in part of Famennian age. A distinctive calcareous siltstone–shale lithology within this series (Plate 2) has been recognised at four localities in our area. Selwood (1958) has discovered fossils of the Tournaisian *Gattendorfia* Zone in beds of similar lithology exposed in a quarry at Yeolmbridge near Launceston. It would thus appear that the Transition Series occupies the position of passage beds between the Devonian and the Carboniferous.

The palaeogeographical interpretation of the Transition Series is of considerable interest. The angular nature of the detrital quartz in the siltstones suggests very little transport of material, whilst the abundant lamellibranchs in the South Brentor Beds, which are frequently preserved with both valves side by side, indicate quiet conditions of deposition. It may be that these strata were deposited in relatively shallow water in contrast to the deeper-water conditions suggested by the older Upper Devonian Slates and the younger Lower Culm Measures.

The two main outcrops of the Lower Culm show important facies changes. Igneous activity was undoubtedly dominant during the deposition of the Lower Culm. In the Meldon district a considerable thickness of pyroclastic deposits is confined to the older Shale-and-Quartzite Group, whilst in the Petertavy district pyroclastics are mainly found in the Calcareous Group and in addition lavas occur near the top of this group. It is thought likely that the injection of sills into the Lower Culm Measures in the Petertavy district took place whilst the sediments were still wet and largely unconsolidated. The main horizon of limestone development in the Calcareous Group of the Meldon district is at the base with a small thickness at the top, whereas in the Petertavy district thin limestones have been found only at the top of the group.

Two contrasted facies have been recognised in the Upper Culm Measures, a southern coarse greywacke group being quite distinct from the three northern sandstone groups, although it is not known whether these facies are of the same age.

The orogenic deformation appears to have taken place in one single prolonged episode. No perceptible folding took place either at the end of the Devonian or at the end of the Viséan, since beds of proven Upper Devonian age and the Upper Culm Measures are involved in the deformation. The structural pattern produced in our area by the deformation was one of recumbent zig-zag folds, broken by normal faults parallel to the bedding. Such a pattern implies a continuous north–south horizontal elongation which was maintained by later basic dyke injection in the Meldon district, and by the emplacement of the granite, jointing, and granite dyke intrusion.

A change in the overall stress conditions was brought about only at the onset of post-granite breccia-faulting. These breccia-faults originated as normal faults, and some of them later became tear faults. The approximately north–south compression necessary to produce the considerable tear on the Sticklepath Fault was probably Miocene in age.

The interpretation of the pre-granite structure here advanced explains the juxtaposition of different parts of the stratigraphical succession. The occurrence of locally derived Middle Devonian limestone pebbles in the New Red Sandstone north of South Tawton (Fig. 1), to which Hutchins (1958) has recently drawn attention, is therefore not surprising. It is quite feasible that the Middle Devonian was locally above the present Culm Measures in this vicinity and has since been eroded.

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EXPLANATION OF PLATE

PLATE 2

Photomicrographs of the distinctive siltstone–shale lithology recognised at four localities in the Transition Series, showing the angular to subangular detrital quartz. P.P.L. (× 40).

A. The South Brentor Beds, in the western quarry (480806), 400 yards north of South Brentor Farm. Outside the granite aureole, with calcite cement.

B. The Meldon Slate-with-Lenticles Group, in the Middle Bay of the Railway Quarry (568927) at Meldon. Within the aureole, the calcite cement replaced by pale green amphibole with biotite-rich shale laminae.

C. The River Lyd Slate-with-Lenticles Group, in the disused quarry (515854) on the northern side of the outcrop. Within the aureole, the alteration as in B, but more intense.

D. The River Lyd Slate-with-Lenticles Group, in the railway cutting (502831) on the Launceston line just north of Lydford Station. On the edge of the aureole.

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DISCUSSION

DR. GILBERT WILSON congratulated the Authors on their contribution to the stratigraphy and structure of the ground around Dartmoor, and said how pleased he was to see that the structures which Dr. Dearman had recently described at Meldon and Okehampton could be prolonged westwards. The introduction by the Authors of a 'Transition Series' between the Devonian and the Culm interested him greatly, because this might have an equivalent on the north Cornish coast. He said that he was thinking particularly of the group of dark slates with grit bands near Boscastle: the Boscastle Measures. The boundary between these rocks which are generally accepted as Culm, and the underlying Tredorn Phyllites, which are considered to be Upper Devonian, can be clearly seen in the sea cliffs at Grower Gut and the old California Quarry, about three-quarters of a mile south-west of Boscastle. It has been referred to as an unconformity. There is a sharp colour change between the two rock groups in the coastal exposures, but no obvious local evidence of unconformability; rather the junction appeared to the speaker to be a straightforward stratigraphical one.

Dr. Wilson therefore enquired whether the Authors had any evidence from inland exposures as to the possible age of the Boscastle Measures, and whether these rocks could be correlated with their Transition Series, or indeed with any other group of the Culm in the region around Dartmoor?

DR. SCOTT SIMPSON said that the folds at Meldon lie in line with folds having a similar attitude which can be seen a few miles to the west in the cuttings along the railway line to Bude. The folds in the railway cuttings like those at Meldon are relatively open and not isoclinal. It is more appropriate to compare the Meldon folds with them than with those to the south, at Launceston, which though on a similar stratigraphic horizon lie in a southerly region of totally different tectonic style, namely one of recumbent isoclines. The speaker, therefore, believed that the Meldon folds have never been recumbent. He was inclined to think that there exists an important line of structural discontinuity between the northern region of open folds and the southern area of recumbency.

D. J. SHEARMAN referred to the structure of the Culm seen along the cliff sections south of Bude. Between Bude and Widemouth the axial planes of the folds dip to the north, but south of Widemouth a fault brings up lower beds which are folded into essentially recumbent folds. In the cliffs between Widemouth and Rusey this succession of flat-lying folds can be seen to dip steeply to the north, and on the evidence of sedimentation structures Dr. D. P. Ashwin and the speaker have found that this succession 'youngs' southwards and is overturned. The regional structure of this part of the Culm outcrop appears therefore to be a major anticlinal fold overturned to the south. The belt of flat-lying folds which may be traced inland to the western margin of Dartmoor appears to mark the outcrop of the overturned limb of this major structure of the Culm. The speaker suggested that the progressive change in the attitude of the folds described along the north-western side of Dartmoor might in part at least be the expression of the change in the attitude of the smaller folds in passing from the normal to the overturned limb of this major structure.

The Devonian rocks to the south, seen in the coast section from Newquay to the Camel Estuary, are thrown into folds which overturn to the north in marked opposition to the regional structure of the Culm. In the intervening area, the Boscastle–Tintagel section, Dr. D. P. Ashwin and the speaker have found that the strata are folded into essentially recumbent folds but folded along approximately north–south axes. This folding produced a distinctive lineation, and the speaker enquired whether the Authors had found any north–south lineation or evidence of north–south fold axes in the Devonian south of the Culm outcrop along the west side of Dartmoor.

MR. BUTCHER thanked Dr. Wilson for his kind remarks. Dr. Wilson's own description (1951, *Quart. J. geol. Soc. Lond.*, **106**, 398) of the strata at Boscastle suggested that these beds belonged to the Upper Culm Measures. In following up this suggestion, the Author had examined rocks from the entrance to Boscastle harbour and these compared closely in thin section with rocks from the Author's Whitchurch Down Greywacke Group at Tavistock.

Mr. Butcher confessed that, whilst he had admired Dr. Wilson's (1951) account of the minor structures on the coast, he had always had serious doubts as to Dr. Wilson's interpretation of the major structure, simply because it was not built on a firm stratigraphical foundation.

It seemed to the Author likely that on the coast the main Devonian outcrop is followed to the north by the Upper Culm Measures, which may be inverted. Indeed, Dr. Wilson (1951, 399) remarked that the zig-zag folds in the Culm Measures at Boscastle suggested inversion, but had added: 'This, however, we know has not taken place. . . .' Unfortunately, Dr. Wilson had never said why we knew the beds were not inverted. Inland, as the paper made clear, there is abundant evidence of inverted strata. Farther north on the coast, undoubted Lower Culm cherts occur at Fire Beacon Point (1895, Hinde & Fox, *Quart. J. geol. Soc. Lond.*, **51**, 609). Thus, in general, the picture on the coast appears similar to that seen inland at Tavistock. The Transition Series could certainly be expected to be present as inliers within the Culm Measures north of Boscastle.

DR. DEARMAN, in reply to Dr. Simpson, stated that he appeared to reject entirely the Authors' description and interpretation of the structures. The first exposure in the cutting along the railway line to Bude from Meldon Junction lies two miles north-west of Meldon where the axis of the Upper Culm syncline next to the granite is sensibly horizontal and trends west-south-west. As this structure is followed south-westwards to the area of Southerly Down its attitude changes, and the plunge of the fold becomes south-westerly at up to fifteen degrees. This marks the limit of my map of this structure, but the steeply dipping beds of the Calcareous Group of the Lower Culm immediately to the north of the Upper Culm can be traced on the ground as a continuous band from Meldon, through Lake, Beara Down, Burley Down, to Lew Wood just south of Lewtrenchard. Here the structures are magnificently displayed in quarry sections; the folds are similar to those at Meldon but are recumbent with horizontal axes trending approximately west-south-west. It is on this field evidence that I maintain that the Meldon folds were originally recumbent and have been uplifted by the granite.

My knowledge of the Launceston area is based on the Survey memoir (Reid & others, 1911. The Geology of Tavistock and Launceston, *Mem. geol. Surv. Eng. Wales*) and on reconnaissance work. In the Launceston area the folds are recumbent, and the bedding dips both to the north and to the south at 25 degrees or more. The structural pattern is the same as that described above.

Considering now the major structure of the southern margin of the Culm Measures outcrop of Devon, I would agree with Dr. Simpson that there is, and indeed must be, a change northwards from recumbent folds to folds with either vertical axial planes or axial planes inclined to the north. This change, however, takes place within a one-mile-wide zone immediately to the north of the main Lower Culm inlier of the Meldon Unit, and does not involve either this unit or the Lydford and Petertavy Units farther to the south.

The Authors believe that Dr. Simpson's interpretation is not in accordance with the field evidence.

IN REPLY to Mr. Shearman, Dr. Dearman thanked him for his comparison of the structures exposed in the coast sections with those described by the Authors from the western border of Dartmoor. There is a widespread development of a north–south lineation in the Whitchurch Green Slates of the Foundation Unit and in the shales of the adjacent Whitchurch Down Greywacke Group of the Upper Culm Measures. One isoclinal fold with an approximately north–south axis has also been found in the latter group. The lineation is due to the intersection of cleavage planes, which dip steeply to the east and the west, with the foliation and bedding. The strata in this area were presumably at or near to the base of the pile of recumbent folds which formed the southern limb of the regional anticlinal fold, and hence the north–south linear structures may indicate an east–west flow due to the heavy incumbent load.

The Authors were aware of the significance of the relative lengths of the limbs of the recumbent folds in determining whether the southern limb of the regional anticlinal fold was vertical or overturned to the south, but had been unable to find conclusive evidence on this point. The observations of Dr. Ashwin and Mr. Shearman on the coastal sections were particularly valuable in this respect.

Annual Report of the Council of the Geologists' Association for the Centenary Year 1958

THE CENTENARY YEAR of the Association was commemorated by the publication of a volume entitled *The Geologists' Association 1858–1958*, edited by G. S. Sweeting. A series of geological guides, edited by Dr. A. K. Wells, was also initiated and ten were published during the year.

Three Centenary Year Lectures were delivered, and there were a large number of Field Meetings, all well attended.

The Reunion was held on 10 November in the apartments of the Royal Society and the Geological Society of London by courtesy of their respective Councils; over 530 members and friends were received by the President and Mrs. Williams. A catalogue describing the thirty-six exhibits was issued.

At the Centenary Dinner in the Connaught Rooms, London, W.C.1, on 11 November, 231 members and guests were present. The President was in the Chair and among the principal guests were the President of the Geological Society, Dr. C. J. Stubblefield, the Director-General of the Nature Conservancy, Mr. E. M. Nicholson, Professor Pruvost (Sorbonne), Professor Holtedahl (Oslo), Dr. A. Ruttner (Austrian Geological Survey), and several Honorary Members, including Mr. W. P. D. Stebbing, a member of the Association for sixty-five years. After dinner speeches were made by Dr. Stubblefield, Professor Williams (President), Mr. C. W. Wright (Vice-President), and Mr. E. M. Nicholson.

Thanks are due to the members of the Centenary Committee and its sub-committees, who devoted much time and thought in planning the Centenary Year programme.

The membership increased by 125 during the year, reaching the record total of 2075.

MEMBERSHIP

The numerical strength of the Association on 31 December 1958, was as follows:

Honorary Members	23	(19)
Ordinary Members:		
Life Members (compounded) ...	181	(179)
Annual Subscribers	1819	(1699)
Institutional Members	52	(53)
	2075	(1950)

(Corresponding figures for 31 December 1957 in brackets)

During the year 215 new members were elected, and the Association lost 100 members through death, resignation, and removals under Rule XI for failure to pay subscriptions. Ten members were reinstated.

The list of deceased members is as follows:

W. J. Arkell, A. L. Armstrong, H. Bury, D. Coy, G. S. Dewey, J. F. Hayward, M. L. Larman, A. M. MacCarthy, John Parry, W. H. Steele, Marie C. Stopes, W. S. Thurlow, S. H. Warren, and H. J. Wilson.

Obituary Notices are published on pages 113–24.

HOUSE LIST

Dr. L. R. Cox retires as Senior Vice-President and Professor Hollingworth, Mr. Montford, Dr. Strachan, and Mr. Baden-Powell as ordinary members of the Council. Thanks are due to these members for valuable services rendered to the Association.

Mr. L. J. Pitt, who has been Treasurer since 1953, resigns from this office at his own request due to pressure of business. He has looked after the financial affairs of the Association very efficiently during a difficult period and particularly during the Centenary Year 1958. He deserves the most cordial thanks of all members of the Association.

FINANCE

The year ended with a deficit on the General Purposes Fund of £53 18*s*. 8*d*. against a deficit at the beginning of 1958 of £476 14*s*. 4*d*. The ordinary income was substantially the same as in 1957 but no grant was received from the Royal Society. The reduction in the deficit is almost entirely due to the publishing of smaller parts of the PROCEEDINGS and credit must be given to the Editor for finding several ways of reducing production costs.

During the year the largest gift in the Association's history was received from one of the Vice-Presidents, Mr. D. Curry, viz. 10,000 five-shilling shares in Messrs. Currys Ltd. A legacy of £25 under the will of a late Honorary Member, Mr. A. L. Leach, was also received.

The 'deficit' in the Centenary Fund is a cash one and should eventually be met by sale of the Guides and the History already published. Meantime the cash position is taken care of by the realisation of securities of the Bequest and Johnston & Howarth Funds, shown in these funds as 'Uninvested Capital'. (These are legacies left to the Association without restriction.)

Early in the year Council appointed a Finance Committee consisting of the President, Secretary, Editor, Treasurer, and Messrs. P. Evans, D. Curry, and Professor Sutton to deal with finance matters before discussion in Council and this has proved very useful. The accounts for this year have been prepared by Mr. J. Carmichael, a member who has taken on the duties of Honorary Accountant to the Association, and thanks are due to him for offering to do this work.

1957		CAPITAL		REVENUE	TOTAL
		Invested	*Uninvested*		
£		£ *s.* *d.*	£ *s.* *d.*	£ *s.* *d.*	£ *s.* *d*
	FUNDS FOR SPECIAL PURPOSES:				
	Bequest Fund	3626 14 0	162 13 0		3789 7 0
	Compounding Fund	2267 9 7	16 0 0		2283 9 7
	Illustrations Fund	120 0 0			120 0 0
	Indexing Fund			12 16 4	12 16 4
	Watts Charnwood Forest Fund			185 3 6	185 3 6
	TRUST FUNDS:				
	Foulerton Award Fund	294 11 0		16 1 2	310 12 2
	Henry Stopes Memorial Fund ...	260 12 9		18 7 8	279 0 5
	Johnston and Howarth Fund ...	1495 0 0	455 8 7	205 9 7	2155 18 2
	G. W. Young Geological Investigation Fund			35 9 7	35 9 7
6781		8064 7 4	634 1 7	473 7 10	9171 16 9
	GENERAL FUNDS:				
117	Subscriptions paid in advance ...				142 0 0
	Overdrawn Petty Cash accounts				1 6 1
	Sundry Creditors (As purchases journal)				210 17 7
	Estimated Accrued Expenses ... (Printing Monthly Circular £35 0 0 Issues of PROCEEDINGS £500 0 0)				535 0 0
	Cash overdraft on Centenary Fund				1750 17 6
					£11,811 17 11

1957				
£		£ *s.* *d.*	£ *s.* *d.*	£ *s.*
6002	Investments		8064 7 4	
22	Income Tax Recoverable		27 15 6	
757	Cash at Bank		1079 13 11	
				£9171 16
	GENERAL FUNDS:			
125	Estimated Value of Arrears of Subscriptions (Book Value £283 15 3)		125 0 0	
–	Petty Cash in hands of officers		20 6 2	
–	Collections in hands of officers at 31 December 1958		318 17 6	
	Estimate of Accrued Income to 31 December 1958:			
	For Advertising	60 0 0		
	For Sales of Guides	160 0 0		
60	For Sales of History	30 0 0		
			250 0 0	
1000	Investment of Centenary Fund		1000 0 0	
455	Cash in Hand on Income and Expenditure Account		121 1 4	
477	Deficit on Income and Expenditure Account ...		53 18 8	
–	Deficit on Centenary Fund		750 17 6	
				£11,811 17 1

CASH RECONCILIATION

Overdraft—Centenary		1750 17 6
Less Cash in Hand—Capital ...	1079 13 11	
Income and Expenditure ...	121 1 4	
		1200 15 3
Overdrawn Balance in Bank Account		£550 2 3

Income and Expenditure Account for the Year Ended 31 December 1958

Statement 2

EXPENDITURE

1957 £		£ s. d.	£ s. d.
	DEFICIT AT 31 DECEMBER 1957 BROUGHT FORWARD		476 14 4
2497	'PROCEEDINGS' OF THE ASSOCIATION: (including Estimated Additional Expenditure of £500 for remaining parts of Vol. 69)		1069 17 9
	GENERAL EXPENSES:		
40	Meetings	44 16 3	
321	Printing Monthly Circular (including accrued expenditure of £35)	302 6 8	
234	Printing and Stationery	160 16 6	
389	Postages	307 6 4	
45	Typing and Duplicating	31 4 11	
37	Accountancy	Nil	
Nil	Binding Volumes of 'PROCEEDINGS' ...	20 1 0	
22	Sundries	9 6 3	
			875 17 11
			£2422 10 0

INCOME

1957 £		£ s. d.	£ s. d.
1681	ANNUAL SUBSCRIPTIONS: (Including £125 being estimated value for book arrears of subscriptions of £283 15 3 at 31 December 1958)	1735 11 8	
66	ADMISSION FEES	96 10 0	
300	ROYAL SOCIETY GRANT	Nil	
60	ADDITIONAL INCOME FROM ADVERTISEMENTS FOR 1957 (and estimated income of £60 for Advertisements in Vol. 69 of PROCEEDINGS	92 13 2	
350	SALES OF PUBLICATIONS (other than Centenary Publications)	292 14 4	
68	INCOME FROM ILLUSTRATIONS FUND	31 15 3	
51	INCOME FROM BEQUEST FUND	45 12 5	
78	INCOME FROM COMPOUNDING FUND	73 14 6	
			2368 11 4
	DEFICIT AT 31 DECEMBER 1958 CARRIED FORWARD		53 18 8
			£2422 10 0

Funds for Special Purposes

CENTENARY FUND

Statement 3

		£ s. d.
EXPENDITURE:		
De la Beche Memorial Plaque		10 0 0
Centenary Reunion		148 16 3
Centenary Dinner	377 19 10	
Less Subscriptions	293 17 6	
		84 2 4
Printing History of the Association		860 19 2
Printing 10 Geologists' Association Guides and preliminary expenditure on printing of 7 further Guides		1247 3 7
		£2351 1 4

	£ s. d.
Balance at 1 January 1958 Brought Forward:	
Invested	1000 0 0
Accumulated Income Uninvested	218 14 10
INCOME:	
Interest from Investments	45 0 0
Sales of History (including estimated additional income to 31 December 1958 of £30)	135 15 0
Sales of Geologists' Association Guides (including estimated additional income to 31 December 1958 of £160)	200 14 0
	1600 3 10
Deficit at 31 December 1958 (which should be liquidated by future sales of Guides and Histories)	750 17 6
	£2351 1 4

(N.B. £1000 Investment of Centenary Fund was still invested at 31 December 1958 resulting in a cash overdraft at 31 December 1958 of £1750 17 6.)

BEQUEST FUND

Statement 4

	Uninvested Capital £ s. d.	Revenue £ s. d.
Transfer to Income and Expenditure Account ...		45 12 5
New Investment	2500 0 0	
Balance Carried Forward (Uninvested Capital at 31 December 1958)	162 13 0	
	£2662 13 0	£45 12 5

	Uninvested Capital £ s. d.	Revenue £ s. d.
Balance at 1 January 1958	Nil	Nil
Investment Income		45 12 5
Sale of Investment	137 13 0	
Bequests	2525 0 0	
	£2662 13 0	£45 12 5

COMPOUNDING FUND

Statement 5

	Uninvested £ s. d.	Revenue £ s. d.		Uninvested Capital £ s. d.	Revenue £ s. d.
Transfer to Income and Expenditure Account ...		73 14 6	Balance at 1 January 1958	128 0 0	Nil
Invested in £177 11 4 6% New Zealand Stock ...	180 0 0		Investment Income		73 14 6
Balance Carried Forward (Uninvested capital at 31 December 1958)	16 0 0		Compounding Fees Received	68 0 0	
	£196 0 0	£73 14 6		£196 0 0	£73 14 6

ILLUSTRATIONS FUND

Statement 6

	£ s. d.		£ s. d.
Transfer to Income and Expenditure Account ..	31 15 3	Balance at 1 January 1958	Nil
		Investment Income	5 9 0
		Donations and Subscriptions	26 6 3
	£31 15 3		£31 15 3

INDEXING FUND

Statement 7

	£ s. d.		£ s. d.
Balance at 31 December 1958	12 16 4	Balance at 1 January 1958	12 16 4
	£12 16 4		£12 16 4

WATTS CHARNWOOD FOREST FUND

Statement 8

	£ s. d.		£ s. d.
Balance at 31 December 1958	185 3 6	Balance at 1 January 1958	185 3 6
	£185 3 6		£185 3 6

TRUST FUNDS

FOULERTON AWARD FUND

Statement 9

	£ s. d.		£ s. d.
Award to R. Reeley	10 0 0	Balance at 1 January 1958	15 11 7
Balance at 31 December 1958	16 1 2	Investment Income	10 9 7
	£26 1 2		£26 1 2

HENRY STOPES MEMORIAL FUND

Statement 10

	£ s. d.		£ s. d.
Engraving Medal	12 6	Balance at 1 January 1958	53 0 8
Award to Dr. Leakey	21 0 0	Investment Income	7 19 6
Award to Henry Dewey	21 0 0		
Balance at 31 December 1958	18 7 8		
	£61 0 2		£61 0 2

JOHNSTON AND HOWARTH FUND

Statement 11

	Capital	Revenue £ s. d.		Capital £ s. d.	Revenue £ s. d.
Album for Photographic Records—Wallace Heaton...		9 9 8	Balance at 1 January 1958	1990 8 2 (Invested)	132 14 2
Original cost of £497 3 5 5% Agricultural Mortgage Corporation Debenture Stock 1979/83	495 8 2		Investment Income		90 8 0
Loss on Field Meetings		8 2 11	Sale of £497 3 5 5% Agricultural Mortgage Corporation Debenture Stock 1979/83:		
Balance Carried Forward (Invested)	1495 0 0		Cash Received	455 8 7	
Uninvested at 31 December 1958	455 8 7	205 9 7			
	£2445 16 9	£223 2 2		£2445 16 9	£223 2 2

G. W. YOUNG GEOLOGICAL INVESTIGATION FUND

Statement 12

	£ s. d.		£ s. d.
Award to W. D. I. Rolfe	15 0 0	Balance at 1 January 1958	32 10 11
Balance at 31 December 1958 Carried Forward	35 9 7	Income from Public Trustee (Two Years)	17 18 8
	£50 9 7		£50 9 7

Statement 1

SCHEDULE OF INVESTMENTS—31 DECEMBER 1958

	AT COST OR PAR VALUE WHEN ACQUIRED				INVESTMEN INCOME (GROS	
	£	s.	d.		£	s.
FUNDS FOR SPECIAL PURPOSES:						
Centenary Fund:						
£1000 4½% Defence Bonds (Due for encashment) 6/4/59 (£600) 27/5/59 (£400)	1000	0	0		45	0
Bequest Fund:						
£143 8 9 3½% War Stock	141	14	0		5	0
£85 0 0 3% Defence Bonds (Due for encashment 6/4/59)	85	0	0		2	11
£100 0 0 3% Savings Bonds 1960/70 ...	100	0	0		3	0
£441 5 4 3% British Transport Guaranteed Stock 1978/88	400	0	0		13	4
£224 13 3 4½% British Electricity Guaranteed Stock 1974/79	200	0	0		9	11
£200 0 0 3½% Defence Bonds (Due for encashment 6/4/59)	200	0	0		7	0
10,000 Shares Currys Ltd. at 5*s*. ...	2500	0	0	New Investment	Nil	
				Income from Investments sold during the year £150 3½% New Zealand Stock 1960/64	5	5
	£3626	14	0		£45	12
Compounding Fund:						
£1217 2 6 3% Irredeemable Nottingham Corporation	1152	13	2		36	10
£200 0 0 3% Savings Bonds 1955/65 ...	200	0	0		6	0
£170 0 0 3½% War Stock	152	14	5		5	19
£100 0 0 3% Savings Bonds 1965/75 ...	100	0	0		3	0
£300 0 0 3½% Treasury Stock 1977/80 ...	282	2	0		10	10
£224 13 3 4½% British Electricity Stock 1974/79	200	0	0		9	11
£177 11 4 6% New Zealand Stock 1976/80	180	0	0	(Part year only)	2	4
	2267	9	7		73	14
Illustrations Fund						
£21 0 10 3% Metropolitan Water Board 'B' Stock	20	0	0			12
£113 13 1 British Electricity 4½% Guaranteed Stock 1974/79	100	0	0		4	16
	120	0	0		5	9
TRUST FUNDS:						
Foulerton Award Fund:						
£349 7 0 3% British Transport Guaranteed Stock 1978/88	294	11	0		10	9
Henry Stopes Memorial Fund:						
£265 19 2 3% Newfoundland Government 1943/63	260	12	9		7	19
Johnston and Howarth Fund:						
£1236 4 6 3½% War Stock	1000	0	0		43	5
£495 0 0 4½% Defence Bonds (Due for encashment 27/5/59)	495	0	0		22	5
				Income from Investments sold during the year £497 3 5 5% Agricultural Mortgage Corporation Debenture Stock 1979/83	24	17
	£1495	0	0		£90	8

J. CARMICHAEL, *Hon. Accountant.*

We have compared these Statements with the books and records presented to us and find them to agree. We have also verified the Investments and Cash Balances held by the Association at 31 December 1958

L. J. PITT, *Treasurer*
7 February 1959.

H. W. BALL
F. J. W. HOLWILL } *Auditors.*

REPORT OF THE SESSION 1958

TRUSTEES

The Trustees of the Association were:

Managing: Dr. W. F. Fleet, M.SC., A.R.I.C., A.C.P., F.G.S., Mr. Percy Evans, M.A., F.G.S., and Dr. W. A. Macfadyen, M.C., M.A.

Custodian: The Royal Bank of Scotland, Western Branch.

PUBLICATIONS

Publications Committee. The Committee consisted of the seven officers with Messrs. H. W. Ball, D. F. W. Baden-Powell, D. Curry, S. E. Hollingworth and J. Sutton. Dr. J. Watson joined the Committee in June to act as secretary in the temporary absence of Dr. Ager.

The Committee met on seven occasions and considered thirty papers, of which eighteen had been recommended for publication by the end of the year.

Proceedings. The remaining two parts of Volume 68 (for 1957), consisting of 135 pages and one plate, making a total of 312 pages and six plates for the volume, were published.

The first three parts of Volume 69 made up of 190 pages and two plates were completed during the year. Part four will be published early in 1959 and the four parts of Volume 70 will be published during the same year.

MEETINGS

Nine Ordinary Meetings and one Special General Meeting were held, at which three Centenary Year Lectures were given, eight papers were taken as read and four other lectures were given. Mr. C. W. Wright, M.A., F.G.S., took the Chair at the first two meetings, and Professor D. Williams, D.SC., Ph.D., M.I.M.M., F.G.S., at the remaining seven ordinary meetings and at the Special General Meeting.

The thanks of the Association are due to the lecturers and especially to the Centenary Year Lecturers, Professors H. H. Read, T. Neville George and S. W. Wooldridge, to the authors of papers and to the Geological Society for the use of its apartments throughout the year.

The names of the 215 members elected in 1958 appeared in Circulars numbered 599–608.

3 *January*. Lecture: ‘The Long Field Meeting in Austria, 1957’, by J. M. Hancock and P. E. Kent.

7 *February*. Lecture: ‘The Geology of Northern Persia’, by Francis Jones, J. L. Knill and C. D. W. Savage.

7 *March.* Annual General Meeting followed by Ordinary Meeting.

11 *April.* Lecture: 'Gravity Structures and Aspects of Geomorphology in West Pakistan', by Professor W. D. Gill. Papers read in title only: 'The Glacial Deposits Around Hertford', by K. M. Clayton and Joyce C. Brown. 'The Clays and Heavy Minerals of the Shotover Ironsand Series', by John C. M. Taylor.

2 *May.* A Centenary Year Lecture on 'Stratigraphy in Metamorphism', by Professor H. H. Read. Papers read in title only: 'An Unrecorded Section in the Purbeck of the Vale of Wardour', by S. W. Hester. 'On the Portlandian Zones of the Vale of Wardour and the use of *Titanites Giganteus* as an Upper Jurassic Zone Fossil', by Michael R. House. 'Subdivision of the Weald Clay in Sussex', by J. W. Reeves.

6 *June.* The Henry Stopes Memorial Lecture for 1958, 'Some Palaeolithic Deposits of the Thames at Dartford Heath and Swanscombe, North Kent', read by K. P. Oakley on behalf of Henry Dewey, F.G.S. The Henry Stopes Memorial Lecture for 1955, 'Chellean Man at Olduvai', by L. S. B. Leakey.

4 *July.* 'A Centenary Year Lecture on the Concept of Homoeomorphy', by Professor T. Neville George. Papers read in title only: 'The Petrology of the Carboniferous Rocks near Stranraer, Wigtownshire', by J. G. C. M. Fuller. 'The Lower Greensand in the Hindhead Area of Surrey and Hampshire', by L. Knowles and F. Middlemiss.

10 *October.* Special General Meeting. A Centenary Year Lecture on 'The Pleistocene Succession in the London Basin', by Professor S. W. Wooldridge.

10 *November.* Ordinary Meeting followed by the Centenary Year Reunion.

5 *December.* Lecture: 'Some Problems of the Geology of Iceland', by Dr. G. P. L. Walker. Paper read in title only: 'Palaeomagnetism of the Younger Gabbros of Aberdeenshire and its Bearing on their Deformation', by D. J. Blundell and H. H. Read.

At the January meeting Drs. C. F. Tozer and H. W. Ball were elected Auditors of the accounts for 1957.

The Annual General Meeting was held on 7 March 1958. C. W. Wright, M.A., F.G.S., President, in the Chair.

The Annual Report of the Council (previously circulated) was taken as read. It was moved by Dr. R. E. Blackith and seconded by Mr. J. A. Dell, 'That the Report of the Council, including the Statement of Accounts, be adopted as the Annual Report of the Association for 1957'. The resolution was carried *nem. con.*

The President declared the following members duly elected as Officers and Members of Council in accordance with Rule XIII: *President*, David

Williams, D.SC., Ph.D., M.I.M.M., F.G.S.; *Vice-Presidents*, L. R. Cox, O.B.E., M.A., SC.D., F.R.S., F.G.S., A. J. Dollar, B.SC., Ph.D., A.K.C., F.R.S.E., F.G.S., D. Curry, M.A., F.G.S., A. K. Wells, D.SC., F.G.S., C. W. Wright, M.A., F.G.S.; *Treasurer*, L. J. Pitt, F.G.S.; *Secretaries*, General—F. H. Moore, B.SC., Ph.D., F.G.S.; Field Meetings—J. M. Hancock, M.A., Ph.D., F.G.S.; Publications Committee—D. V. Ager, B.SC., Ph.D., D.I.C., F.G.S.; *Editor*, G. T. Raine, B.SC., A.M.Inst.Pet., F.G.S.; *Librarian*, R. Bradshaw, M.SC., F.G.S.; *Twelve other Members of Council*, S. E. Hollingworth, M.A., D.SC., F.G.S., H. M. Montford, O.B.E., B.SC., Isles Strachan, B.SC., Ph.D., F.G.S., D. F. W. Baden-Powell, M.A., B.SC., F.G.S., S. W. Hester, F.G.S., W. S. Pitcher, Ph.D., B.SC., D.I.C., F.G.S., N. B. Peake, F.G.S., M. K. Wells, M.SC., Ph.D., F.G.S., Mrs. J. N. Carreck, G. F. Elliott, F.G.S., John Sutton, B.SC., Ph.D., A.R.C.S., F.G.S., Miss M. A. Arber, M.A., F.G.S., F.R.G.S.

It was moved by Mr. J. N. Carreck, seconded by Mr. R. C. Sanson and duly carried, 'That the best thanks of the Association be given to the retiring President, the Officers, the retiring Members of Council and the Auditors'.

On the nomination of Council, Professor Georges Delépine, Godfrey Wilfred Himus, Ph.D., F.G.S., John Ranson, A.M.I.Min.E., F.G.S., Professor Herbert H. Read, D.SC., F.R.S., A.R.C.S., F.G.S., Dr. A. Ruttner and Alfred Kingsley Wells, D.SC., F.G.S., were elected Honorary Members of the Association.

The Henry Stopes Memorial Medal for 1958 was conferred on Mr. Henry Dewey in recognition of his work on the Prehistory of Man. Dr. K. P. Oakley received the medal on his behalf.

The President said:

> Dr. Oakley: We are all sorry that Mr. Dewey cannot be with us today to receive in person the Henry Stopes Memorial Medal but we ask you to carry to him our congratulations and best wishes.
>
> Throughout his long career on the Geological Survey and during his retirement Mr. Dewey has been an active student and writer on the gravels and other quaternary deposits that contain evidences of Palaeolithic man. I am happy to hear that he is still carrying on this work in Devonshire.
>
> His paper, with R. A. Smith, in our PROCEEDINGS in 1914 on the Palaeolithic Sequence at Swanscombe, is a landmark in our understanding of these important deposits. It is therefore with lively anticipation that we look forward to hearing Mr. Dewey's Stopes Memorial Lecture on 'Some Palaeolithic Deposits of the Thames at Dartford Heath and Swanscombe, North Kent'.
>
> Mr. Dewey was our President from 1924–6, years in which I can just say with truth that I was a geologist, for I was collecting devil's-toenails and other fossils from the Yorkshire Boulder Clay. The range of his interests is shown by his Presidential Addresses on Danish Geology and on Mineral Zones of Cornwall.
>
> It is twenty-five years since Mr. Dewey received the Lyell Medal of the Geological Society and I have great pleasure in handing to you, Dr. Oakley,

> for transmission to Mr. Dewey, the Henry Stopes Memorial Medal of the Geologists' Association.

The Foulerton Award and Certificate were presented to Mr. R. Reeley, in recognition of work of merit connected with the Association.

The President said:

> Mr. Reeley: The Foulerton Award is given for services to the Association. You have conspicuously deserved it. You have the second longest term of office as General Secretary of the Association and have served under six Presidents. All of them, I am sure, have appreciated the efficiency, thoroughness and diplomacy with which you carried out your task.
>
> During your term of office, membership of the Association increased from 1300 to over 2000. Only a General Secretary knows what this means in terms of work behind the scenes.
>
> You still give the officers valuable advice from the fund of your experience and I hope that you will long continue to do so.
>
> Outside our own field, you have rendered geologists at large a great service by your work in charge of the library at the Geological Survey. Not only the staff of the Survey but many other geologists and enquirers have cause to be grateful for your help.
>
> It is with great pleasure that I present you with the Foulerton Award.

The President then delivered his address entitled, 'Order and Disorder in Nature'.

It was moved by Mr. E. E. S. Brown, seconded by Miss E. W. Andrews, and duly carried, 'That the best thanks of the Association be accorded the President for his Address'.

FIELD MEETINGS 1958

The Committee consisted of the seven officers with Messrs. D. F. W. Baden-Powell, J. S. H. Collins, D. Curry, S. W. Hester, J. F. Kirkaldy, F. Middlemiss, H. M. Montford, N. Peake and D. Shearman.

For the Centenary Year more Long Field Meetings than usual were held. There were three meetings at Easter—in the Isles of Scilly, a study of the Mineralogy of Cornwall and in the Weymouth district—but there was no meeting at Whitsun. During the summer visits were made to North Scotland and the Welsh Borderland and a study was made of the Pleistocene and Pliocene of East Anglia.

Four Demonstrations, one week-end, six whole day and five half-day Field Meetings were held during the year. Two of these short meetings repeated the first two Field Meetings held by the Association.

The thanks of the Association are due to the Directors and all others who organised and helped to make these meetings a success.

The following Field Meetings and Demonstrations took place:

15 *February*. Demonstration on the Extraction, Cleaning and Preservation of Fossils at the Geological Survey, arranged by Dr. F. W. Anderson.

22 *February*. Demonstration on the Extraction, Cleaning and Preservation of Fossils at the Department of Palaeontology, British Museum (Natural History), arranged by Mr. A. E. Rixon.

22 *March*. Visit to Imperial College Geophysical Field Station, Silwood Park, at the invitation of Professor J. M. Bruckshaw and his colleagues of the Department of Geophysics at Imperial College.

31 *March*–4 *April*. Easter Field Meeting in the Isles of Scilly. Director, Dr. A. T. J. Dollar.

4–7 *April*. Easter Field Meeting to study the Mineralogy of Cornwall. Director, Dr. K. F. G. Hosking.

3–8 *April*. Easter Field Meeting at Weymouth. Director, Mr. M. R. House.

26 *April*. First of three Field Meetings to illustrate the changes of facies occurring within the Lower Tertiary of the London Region: North Kent—Upnor and Herne Bay. Director, Dr. W. S. Pitcher.

10 *May*. First of two Field Meetings to demonstrate the variations in the Cretaceous Rocks of the Weald: West Surrey and West Sussex. Directors, the Reverend J. W. Reeves and Dr. J. F. Kirkaldy.

24 *May*. Second of the three Field Meetings on the Lower Tertiary of the London Region: Charlton and Abbey Wood. Director, Dr. W. S. Pitcher.

7 *June*. Second of the two Field Meetings on the Cretaceous of the Weald: East Surrey and West Kent. Director, Dr. J. F. Kirkaldy.

21 *June*. Field Meeting at the Iguanodon Quarry, Maidstone, being a repeat of the second Field Meeting held by the Association, Tuesday, 19 June 1860. Director, Dr. W. E. Swinton.

6 *July*. Field Meeting at Colney Heath. Directors, Professor S. W. Wooldridge and Dr. E. H. Brown.

12 *July*. The third of the three Field Meetings on the Lower Tertiary of the London Region: Harefield. Director, Mr. S. W. Hester.

26 *July*. Field Meeting at Hertford. Director, Mr. K. M. Clayton.

2–9 *August*. Summer Field Meeting in the Welsh Borderland. Organising Director, Dr. J. D. Lawson, assisted by Mr. R. Allender, Dr. C. H. Holland, Dr. V. G. Walmsley and Mr. J. H. McD. Whitaker.

11–25 *August*. Summer Field Meeting in North Scotland. Directors, Drs. A. T. J. Dollar and Vernon Wilson, Professor T. S. Westoll and Dr. T. Robertson.

14–24 *August*. Summer Field Meeting to study the Pleistocene and Pliocene of East Anglia. Directors, Mr. D. F. W. Baden-Powell and Dr. R. G. West, assisted by Mr. P. Cambridge, Dr. G. P. Larwood and Mr. H. E. P. Spencer.

31 *August*. Field Meeting at Swanscombe and Northfleet, Kent. Director, Mr. J. N. Carreck.

14 *September*. Field Meeting at Folkestone, being a repeat of the first

Field Meeting held by the Association, Monday, 9 April 1860. Director, Dr. R. Casey.

19–21 *September*. Week-end Field Meeting at Cambridge. Director, Dr. C. L. Forbes.

4 *October*. Field Meeting at Selborne to study the geology of Gilbert White's country. Director, Dr. F. A. Middlemiss.

6 *December*. Visit to the Evolution Exhibit at the British Museum (Natural History). Demonstrated by Mr. A. Leutscher.

NORTH-EAST LANCASHIRE GROUP

Chairman, J. Ranson, A.M.I.Min.E., F.G.S.; Secretary, Mrs. J. F. Ranson, B.A.; Committee, H. E. James, B.A., B.SC., F.R.G.S., D. H. Learoyd, B.SC., F.G.S., A. Moore, B.SC., S. Westhead, I. A. Williamson, B.SC., F.G.S.

During the year seven meetings were held and there were six Field Meetings.

24 *January*. 'The Lower Clyde Valley', by D. H. Learoyd.

21 *February*. 'The Cumberland Coast', by J. Ranson.

14 *March*. 'Lower Carboniferous Reefs of Northern England', by Dr. D. Parkinson.

18 *April*. 'About Limestones', by I. A. Williamson.

17 *May*. Field Meeting: 'Clitheroe and Pendle Hill.' Director, S. Westhead.

7 *June*. Field Meeting: 'The Hillhouse Coastline.' Director, H. E. James.

21 *June*. Field Meeting: 'Upper Ribblesdale.' Director, J. Ranson.

12 *July*. Field Meeting: 'The North Craven Fault (1).' Director, I. A. Williamson.

23 *August*. Field Meeting: 'The North Craven Fault (2).' Director, I. A. Williamson.

27 *September*. Field Meeting: 'Darwen Moor.' Director, D. H. Learoyd.

24 *October*. The thirty-fifth Annual General Meeting. Résumés of the Field Meetings were given by the various directors.

14 *November*. 'Mineral Prospecting in British Columbia', by J. S. Shackleton.

5 *December*. 'The Cumberland Coast. Part II', by J. Ranson.

Thanks are due to the Blackburn Education Authority and the Governors and Principal of the Technical College for the use of rooms.

MIDLAND GROUP

Chairman, H. Sanders; Secretary, Dr. I. Strachan, B.SC., Ph.D., F.G.S.; Committee, Miss G. M. Bauer, Mrs. H. Bone, H. D. Brook, Dr. J. D. Lawson, Ph.D., F.G.S., Dr. W. Tennent, M.D.

Five indoor meetings and five Field Meetings were held.

25 *January*. Dr. J. H. Callomon on 'Some Problems of Jurassic Stratigraphy studied during the 1957 Danish NE. Greenland Expedition'.

8 *March*. Dr. Vernon Wilson on 'Geological Surveying and the Making of a Geological Map'.

29 *March*. Excursion to Newbury Lane Brick Pits. Director, Mr. Hardie.

2–4 *May*. Week-end visit to Church Stretton. Director, Mr. Whitehead.

21 *June*. Whole-day excursion to South Malverns. Director, Dr. G. T. Warwick.

27 *September*. Excursion to the Wren's Nest. Director, Dr. I. Strachan.

18 *October*. Address by the Chairman, H. Sanders, on 'The Colorado River'.

15 *November*. Dr. I. Strachan on 'Geology in the Mid-West'.

13 *December*. Film *67° South* and Christmas Party.

Thanks are due to Professor F. W. Shotton for the use of the Geology Department, Birmingham University.

NORTH STAFFORDSHIRE GROUP

Professor F. Wolverson Cope, D.SC., M.I.Min.E., F.G.S.

Chairman, P. S. Keeling, B.SC., A.R.S.M., F.G.S.; Vice-Chairman, C. S. Exley, M.A., D.Phil., F.G.S.; Secretary, T. S. Purcell, B.SC., F.G.S.; Treasurer, J. T. Gleaves, B.A.; Field Secretary, T. S. Jones, F.G.S.; Research Secretary, D. O. Thomas, F.G.S.; Committee, R. Clark, B.SC., Dr. M. J. Farrell, A. B. Malkin, B.SC., J. Myers, B.SC., F.R.G.S., F.G.S., J. C. Parrack, B.SC., F.R.G.S., J. T. Wattison, F.G.S., F.R.E.S.

During the year seven Ordinary Meetings and four Field Meetings were held. The Ordinary Meetings were again held in the Arts Centre, Newcastle under Lyme, but for the Annual Conversazione and Dr. Dollar's lecture, the Group were the guests of Professor Cope in the University College of North Staffordshire.

The 'theme' of Field Meetings throughout the year has been the Carboniferous Limestone.

A considerable number of photographic records of the Group's activities have now been made, and attention is again drawn to the opportunities offered for the recording of temporary sections, and especially in the development of the new motorway in the area. These records should go to the Research Secretary.

The following meetings and Field Meetings were held:

9 *January*. J. Myers on 'The Geology of Pembrokeshire'.

13 *February*. A. J. Dollar on 'Some Seismic and Aseismic Regions of Great Britain' (held in the University College of North Staffordshire).

13 *March*. Annual General Meeting. The Chairman, P. S. Keeling, on 'Clay Minerals'.

10 *April*. Film Evening and Specimen Exchange.

20 *April*. Field Meeting to Carboniferous Limestone of Llanymynech. Director: J. T. Wattison.

18 *May*. Field Meeting to Carboniferous Limestone of Great Orme's Head. Director: T. S. Jones, for Professor Cope.

15 *June*. Field Meeting to Carboniferous Limestone of Eglwyseg, Llangollen. Director, J. C. Parrack.

6 *July*. Field Meeting to Derwent Valley and Edale.

9 *October*. Annual Conversazione, held in the Geology Department of the University College of North Staffordshire.

13 *November*. P. S. Keeling on 'Relations of Wollastonite Deposits to the Rapakiwi Granite, Finland'.

11 *December*. Joint Meeting with the North Staffordshire Field Club. Professor F. Wolverson Cope on 'The Geology of the Roches and Goldsitch Moss'.

JAMAICA GROUP

Chairman, L. J. Chubb, Ph.D., D.Sc., F.G.S.; Vice-Chairman, S. A. G. Taylor; Secretary, E. Robinson, B.Sc.; Treasurer, Kathleen O. Cusack, B.Sc.; Committee, Leila Dutt, B.Sc., Rita O. Stewart, E. L. Frater, B.Sc., V. A. Zans, Mag. rer. nat. habil., F.G.S., C. B. Lewis, B.A., A. Munoz-Bennett.

During the year three meetings were held in addition to the Annual General Meeting, and there were five Field Meetings. Special Centenary activities included the issue of a quarterly newsletter entitled *Geonotes*; the Group's first long Excursion; the unveiling of a bronze plaque at Halse Hall, Clarendon, in honour of Sir Henry Thomas De la Beche; and a Centenary Dinner-Dance. Thanks are due to the Director of the Institute of Jamaica for the use of the Science Library for Committee Meetings.

The following meetings and Field Meetings were held:

2 *February*. Field Meeting: 'The Cretaceous Rocks and Mineral Springs of Bath, St. Thomas.' Director, L. J. Chubb.

28 *February*. Lecture: 'The Earth', by S. A. Vincenz.

7–12 *April*. Easter Field Meeting in St. James and Trelawny. Directors, V. A. Zans, L. J. Chubb, H. R. Versey and E. Robinson.

30 *April*. Lecture: 'Natural Resources Development', by J. B. McClusky.

25 *May*. Field Meeting at Bowden. Director, L. J. Chubb.

27 *July*. Field Meeting: 'Buff Bay and Low Layton.' Director, E. Robinson.

29 *August*. Lecture: 'The Geology of Water', by H. R. Versey.

28 *September*. Field Meeting: 'Dallas and Cane River Falls.' Director, V. A. Zans.

24 *November*. Broadcast: 'The Visit to Jamaica of Sir Henry De la Beche', by S. A. G. Taylor.

4 *December*. Unveiling of the plaque in honour of Sir Henry Thomas De la Beche, at Halse Hall, Clarendon, by His Excellency the Governor of Jamaica, Sir Kenneth Blackburne.

10 *December*. Annual General Meeting, followed by an exhibition by V. A. Zans of colour slides illustrating his recent work on coral-reefs.

11 *December*. Centenary Dinner-Dance at the Courtleigh Manor Hotel.

THE LIBRARY

The Library Committee consisted of the President, Mrs. Evans, Messrs. R. Bradshaw (Librarian), L. R. Cox, M. K. Wells, Gilbert Wilson and J. W. Scott, B.A., A.L.A., Librarian of University College, London. Dr. A. J. Smith succeeded Mr. Bradshaw as the Association's Librarian in May.

The Association acknowledges with thanks the gifts of books and separates listed below.

An exchange of publications has been instituted with the following:

Egyptian Journal of Geology, from the National Research Centre, Dokki, Cairo, Egypt.

Geoloski glasnik, from the National Museum, Sarajevo, Yugoslavia.

Regional Geology and Reports from the Geological Society of Lvov, U.S.S.R.

Works of the Institute of Palaeontology, from the All Union State Library of Foreign Literature, Moscow, U.S.S.R.

Revue de Micropaléontologie, from the Micropalaeontology Laboratory, University of Paris, France.

Acta Geologica Sinica and *Acta Palaeontologica Sinica* from the National Library of Peking, China.

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OBITUARY NOTICES, 1959

WILLIAM JOSCELYN ARKELL died on 18 April 1959, aged fifty-three. He was born and brought up in Wiltshire and was educated at Wellington College and New College, Oxford. He won first class honours in geology in 1925 and thereafter devoted his working life to geological and particularly palaeontological research. Until 1947, except for two years in London during the war when he was employed in the Ministry of Shipping, he lived in or near Oxford; during most of that time he was a research fellow or lecturer at New College. The last twelve years of his life were spent at Cambridge, as a senior research fellow of Trinity.

His first published work, on Corallian lamellibranchs, appeared in 1926, his last, posthumously, on Jurassic ammonites, in 1957. Those thirty years saw the publication of 187 items (some in collaboration). Many were considerable works of great and lasting importance, including monographs on the Corallian lamellibranchs, Corallian ammonites and Bathonian ammonites. Shorter papers covered the whole range of Jurassic studies, structural, stratigraphical, palaeontological and nomenclatorial. They ranged over the whole period and the whole world. Two books which by themselves would have ensured a lasting reputation appeared almost at the beginning and the end of his career. The *Jurassic System in the British Isles* was published in 1933 when Arkell was only twenty-nine and immediately brought him world-wide fame. His *Jurassic Geology of the World* came out in 1956 when he was at the height of his powers. Complementary to the latter work was his contribution on the Jurassic ammonites to volume L (Ammonoidea) of the *Treatise on Invertebrate Palaeontology*, of which volume he was a capable co-ordinator of the various authors. All these works demonstrated a characteristic mastery of detail and ability to synthesise and to produce a clear and completely comprehensible account of a complex subject. Each will for long remain the standard reference book in its field. In particular the *Jurassic Geology of the World* is a masterpiece in the study of Jurassic correlation which is unlikely ever to be superseded.

Many factors entered into Arkell's strength as a geologist and writer: his early grounding in most branches of natural history and in the Jurassic geology of Wiltshire and Oxfordshire, the inspiring teaching of Sollas, his wide and continuing experience in the field, his capacity for work and his uncompromising search for truth. Above all, from his readers' point of view, he took immense pains to write simply and lucidly, so that none need ever be doubtful of his meaning. Almost any one of his papers would serve as a model of scientific writing and all his work is a pleasure to read.

His interests extended far beyond Jurassic geology. He had a deep love of the countryside and was much concerned about its preservation. He was an able entomologist, specialising in Diptera. Four seasons' work in the

Nile Valley between 1926 and 1930 led to a lifelong interest in the Pleistocene and in archaeology.

Arkell served the Association well. There are over twenty papers by him in our PROCEEDINGS. Four of them are reports of Field Meetings which he led. The last of these was in 1946 and few of the present generation therefore are likely to have enjoyed the stimulating experience of being taken by him over some of his favourite ground in Oxfordshire or Dorset. Many, however, of the innumerable students who visit the Dorset coast have met him near his holiday home at Ringstead and have had the privilege of discussing their problems with him.

Arkell was very tall and gave an impression of sternness and distance at first sight but this belied his ready friendliness. He was always outspoken and did not mince words. Some took this habit as an expression of some personal antipathy but they were wrong. Arkell assumed that every scientist wished to reach knowledge and the best possible explanation of phenomena and that frank discussion and argument were the proper means to this end.

His achievements received wide recognition. He was elected a Fellow of the Royal Society in 1947, was awarded the Mary Clark Thomson gold medal by the National Academy of Sciences of America in 1944, the Lyell medal by the Geological Society in 1949 and the von Buch medal by the German Geological Society in 1953 and was a member of many overseas societies. He carried on a wide correspondence with friends and colleagues round the world and his death leaves a gap that will be felt for many years to come. C.W.W.

HENRY BURY died at Bournemouth on 27 March 1958, in his ninety-sixth year. Educated at Eton and Trinity, he took a first in the Natural Science Tripos and in 1888 was elected a Fellow of Trinity. Twenty years later he entered the geological world, joining the Society in 1907 and the Association in 1909. Living near Farnham, he made an intensive study of the gravel beds and the denudation history in the neighbourhood, subjects which at that time aroused little interest in orthodox geological circles, as can be inferred from the length and nature of the discussion which is appended to the second of his two papers in the *Quarterly Journal of the Geological Society* (1908 and 1910). This paper is a thorough and carefully reasoned discussion of the drainage history of the western part of the Weald. Professors Wooldridge and Linton in their well-known monograph on the geomorphological evolution of south-eastern England (1955) pay abundant tribute to Bury's work of nearly forty years before; in particular, his appreciation that the drainage of the Weald must have originated upon a plane of marine denudation cut across the mid-Tertiary folds.

Bury's first papers in the PROCEEDINGS (1913 and 1916) dealt with the gravel beds of Farnham and their palaeoliths. He led Field Meetings to the area in 1913, 1915 and 1916. An old member who attended these meetings remembers Bury as a tall, well-built man who demonstrated the evidence for his conclusions with an air of authority. In a further paper in 1922 he concentrated on the gravels of the Hale Plateau. He equated these gravels, from their situation and nature, with the Lenham Beds of East Kent and made the important deduction that since their deposition the Wealden area could not have been warped along transverse axes. The gravels and palaeoliths of the Farnham area were the subject of his Presidential Address to the Prehistoric Society of East Anglia in 1923.

A move to Bournemouth enabled him to study a new area, including a fresh group of gravels. He contributed papers to Section C when the British Association met at Bournemouth in 1920 and at Southampton in 1926. His major paper on the area is to be found in the PROCEEDINGS for 1933. In this, he postulated an aggradation of over 100 feet covering the degraded bluff, which separates his Upper and Lower Gravel Plains. Three years later he explained a number of anomalies in the drainage pattern of the Isle of Purbeck by superimposition from a veneer of Pliocene deposits, laid down on a plane of marine erosion cut across the strongly folded Jurassic and Cretaceous strata. In 1940 he published with A. S. Kennard a short note in the PROCEEDINGS on some Holocene Deposits at Box (Wiltshire). His last contribution to the PROCEEDINGS, to the discussion on Pleistocene Chronology, was written in his eightieth year, whilst in his eighty-eighth year the Bournemouth Natural Science Society published Bury's account of the Blashenwell Tufa.

Bury's work is characterised by a combination of careful field observation and far-sighted deductions. The importance of his earlier papers was certainly not appreciated until many years after their date of publication, for Bury, an amateur geologist and prehistorian, following his own lines of thought, had developed the outlook of the modern geomorphologist, many years before geomorphology had reached its present status. J.F.K.

JOHN HAYWARD, who died suddenly on 27 January 1958, had been an active member of the Association for nearly twenty years, and was a member of the Council at the time of his death.

Finding that a business career did not give him sufficient opportunities for geological work he had the courage to change his profession, taking his doctorate at London University and becoming a schoolmaster. His enthusiasm, determination and gift of lucid explanation made him a valuable exponent of the subject and the number of men and women, boys and girls, first interested in geology by him must be very considerable. He not only introduced or extended the teaching of geology in the schools with which he was associated, but conducted numerous adult classes, mainly under the auspices of London University.

A firm believer in the value of field work, not only for research, but also as a means of instruction, he frequently organised Field Meetings for the Association and in connection with his classes. Each year he took a party of his students to some geologically interesting part of the British Isles; there his pupils were instructed not only in the geology of the neighbourhood, but also in the art of combining hard living with high thinking.

He considered that the amateur, given the right instruction and direction, could make a valuable contribution to the science, and he not only welcomed assistance in his own work but, not long before his death, he was largely responsible for the organisation of the South-West Essex Geological Group. The members of the Group, many of them his own students, were engaged in preliminary survey work and notification of exposures, under the direction of a band of competent geologists.

He published a number of papers, many of which had been read before the Association. As a biologist he first applied himself to palaeontological problems and wrote several papers on variations in the genus Echinocorys (e.g. 1940, *Proc. Geol. Ass., Lond.*, **51**, 291). Later he devoted himself mainly to the Pleistocene and Holocene geology of Essex and the Lea Valley. He was always quick to take advantage of temporary exposures resulting from building or engineering works, and the construction of the Lea Valley sewer provided him with much valuable material which he summarised in a paper read before the Association (1957, *Proc. Geol. Ass., Lond.*, **68**, 39–44).

His death is a loss both to geological research and to geological teaching. It is also a sad personal loss to the many who will always be grateful for the introduction which he gave them to the subject, and for his advice and assistance which was so readily available. H.A.P.F.

MARK LININGTON LARMAN was born in Southend-on-Sea in 1899, and died on 4 March 1958 at the place of his birth. During the last fifteen years of his life he pursued geology with an enthusiastic zeal such as must have characterised amateurs of earlier decades but is, perhaps, rarer in this present age of sophisticated diversions. He was elected a member of the Association in 1949.

Educated at Mill Hill School, he initially became interested in astronomy, and was a very active member (possessing an observatory in his garden) of the British Astronomical Association, which he addressed on occasion. But it was his belief in the improbability of his ever being able to contribute usefully to that science, with the limited opportunities and apparatus of an amateur, that led him to forsake it. His love of the country and, more particularly, of fell-walking in the Lake District and

North Wales excited his curiosity about the rocks, and it was to his knowledge of the achievements of another enthusiastic amateur—his friend, the late Sir Harold Stiles (whose obituary we published in 1947)—that he perhaps owed his earliest stimulus in that direction. Once stimulated, he pursued the subject with a rare avidity and thoroughness, and at the age of forty-eight undertook a course of study at Chelsea Polytechnic. His interest lay chiefly in igneous and metamorphic rocks, and the writer can well recall him, after one particular fortnight in the field, painstakingly cutting one thin section each morning before breakfast, until he had completed the hundred or so he required!

A devotee of craftsmanship, a man of acute perception, and, above all, one of tireless enthusiasm, he had no time for charlatans, but loved and admired enthusiasm in others. There are many whom he encountered as young students, who will remember the interest which he showed in their work, and the encouragement which he gave to them. This aspect of his personality was inseparable from the humble reverence which he held for those who had had the advantage of a more formal grounding in geology than himself. It was his simple ambition that his own efforts might be of value or service to those more fortunate in their training, and hence in their opportunities to utilise knowledge gained to the benefit of geology as a science. He set himself a target in the perfection of the specimens which he liked to preserve which few amateurs (and not many professionals) attempt to achieve, and the quality of his thin sections was praised by numerous connoisseurs. The bulk of his collection from North-East Scotland, the Lake District, The Lizard, and other classical igneous localities, housed in his original cabinet, is now exhibited in the Geological Department of the Imperial College of Science and Technology—to whom it was presented by his widow.

His presence at our Long Field Meetings was confined to those in Norway (1950) and Italy (1954), but few week-ends (wet or dry, winter or summer) failed to see him in the field. His comparative 'exile' (in Essex) from the crystalline rocks led to an interest in the Chalk of eastern and southern England, and he 'worked' innumerable sections in these areas with the same acute observation and care that he was accustomed to devote to the 'harder' rocks. The owner of a motor yacht, he must have been one of the few members to have been mentioned in our annals as having joined a Field Meeting (in Sheppey, in 1954) after landing at the very foot of the section in his own boat!

His premature death from coronary thrombosis (itself the undoubted result of a life in which he left himself all too little time for relaxation) has robbed the Association of a member whose labours and example would have continued to benefit geologists (and would-be geologists) for many years to come.

N.B.P.

The death, after a short illness, of WILLIAM HERBERT STEELE, at Charing Cross Hospital in November 1958, at the age of sixty-two, saddened many geologists who had known him intermittently for more than twenty years as a member of Field Meetings in various parts of Britain. He joined the Association in 1937.

Mr. Steele was born at Poole, Dorset, and was educated at Parkstone and Poole Grammar School and at Newport Technical College. He entered the electrical industry in the early stages of its development by becoming an articled pupil of the Newport Electricity Department in 1913. In World War I he joined the Royal Flying Corps and after demobilisation held various appointments in electricity supply undertakings, becoming one of the original grid system control engineers of the Central Electricity Board. An important appointment was that of Control Superintendent of South-East England and National Central. He was a Member of the Institute of Electrical Engineers.

But it was as a keen amateur geologist that he was best known to many who shared with him, after office hours and during holidays, an intense love of the subject. He became an evening student at Chelsea Polytechnic in 1951. By 1957 he had become fully proficient in Mineralogy and Petrology and at the time of his death was studying the detrital grains in the Bagshot Sands of Hampstead Heath. His enthusiasm never palled and during field classes his energy, even in the worst terrain, never flagged—nor did he allow it to—before students many, many years his junior. He liked to set an example on behalf of his generation and it was his kindly and ever-boyish spirit which won him many friends and gave him a youthfulness which few could equate with his age. He had one other love—the violin—and was an accomplished member of the Pinner District Orchestra.

Mr. Steele lived at Tithe Walk, Mill Hill, and leaves a widow.

W.E.S.

DR. MARIE STOPES died at her home near Dorking, Surrey, on 2 October 1958, aged seventy-eight. She was the daughter of the archaeologist and anthropologist Henry Stopes. The medal bearing his name was founded by the Geologists' Association in 1946 for work in human prehistory.

Marie Stopes went to school first in Edinburgh and later in London, and won a chemistry scholarship to University College, London. There she won the Gold Medal in Junior and Senior Botany, and graduated under Professor F. W. Oliver. Palaeobotany was then in the exciting phase of development associated with the coal-ball studies which were to culminate in the discovery of the Pteridosperms by Oliver & Scott in 1904. After graduating, Marie Stopes went to Munich and did two years of postgraduate study there under Goebel and Radelkofer on the morphology of living cycad seeds, and there took her Ph.D. Her first paper dealing with a fossil plant was a study of a Cordaite leaf, published in 1903, and for the next twenty years palaeobotany was to be her main field of interest.

In 1904 Dr. Marie Stopes joined Manchester University as the first woman on the scientific staff. During her first three years there she published on several coal-ball plants and on the nature of coal-balls themselves, both on her own and with D. M. S. Watson, her contemporary at Manchester. She also published an account of the Scottish Inferior Oolite flora (1907, *Quart. J. geol. Soc. Lond.*, **63**). In August 1907 she went to Japan in search of palaeobotanical material, centring her work on the Imperial University, Tokio. This was no small adventure in the days when women in academic work were still a novelty, and in the field of geology almost an impropriety. During her two years spent in Japan, Dr. Stopes made a number of expeditions into little-frequented parts of the country in search of fossil plants. She evidently enjoyed the incredulity, tempered with oriental courtesy, with which she was greeted while on her travels. After her return to England, Marie Stopes published a number of papers on her Japanese discoveries, both on her own and with Dr. K. Fujii. The most important of these was a collection of Cretaceous petrified plants, including one of the earliest petrified flowering plant ovaries known. She also published her *Journal from Japan* (1910), which gives a very vivid account of her life there. She deplored the effect of the impact of western ideas and products on the old Japanese culture. This feeling is symbolised in the book that she wrote with Professor J. Sakurai on the *Plays of Old Japan*, in which she eulogises the old culture in this rather esoteric form. Her diversity of interests at that time is illustrated not only by this work, but by a short paper concerning some observations that she made on ants while in Japan.

Dr. Marie Stopes returned to Manchester in 1909 as lecturer in palaeobotany, and the following year published her book on *Ancient Plants*—perhaps the first attempt at a genuinely popular account of the subject. It was typical of her that she was not content merely to carry on palaeobotanical research, but wanted to interest a wider audience in the new discoveries. In 1911 she went to the United States and Canada, principally to study the Carboniferous ‘Fern Ledges’ flora of New Brunswick, on which she published in 1914. This confirmed the Coal Measure age of the plants (at one time reputed to be Devonian, or even Silurian) and also the identity of many of the Canadian plants with species already known from Europe. On returning to England, Dr. Stopes resumed her studies of Cretaceous plants, publishing a two-volume British Museum Catalogue on the Cretaceous Flora (1913–15). Perhaps the most important feature of this work was the account of the petrified woods from the British Lower Greensand, on which she had first published in 1912 (*Phil. Trans.* (B), **85**). These were remarkable in that although they were the earliest angiosperms known from north-west Europe, they proved to be completely modern and specialised in their anatomy, seeming to bear out the suddenness of the rise of the flowering plants early in the Cretaceous.

The last phase of Marie Stopes' palaeobotanical work centred on the composition of coal. She and Professor R. V. Wheeler originated the terminology of clarain, durain, fusain and vitrain which later, in somewhat modified form, gained international acceptance. Between 1919 and 1923, both on her own and jointly with Professor R. V. Wheeler, she published a number of papers on the origin and petrography of coal. Although this work was essentially of an applied nature, Marie Stopes always returned to the theme that the problem of the origin of coal (and so of its constitution) was a palaeobotanical one. After the publication of her several widely read books, and the foundation of her birth-control clinics, Dr. Stopes naturally gave less time to her earlier interests. One of her last works in the field of geology was a re-statement and extension of her ideas on coal petrography published in 1935. Despite her preoccupation with other activities, she retained an active interest in geological (and particularly palaeobotanical) matters all through her life. She found time to follow current work, and was always disposed to take a kindly interest in an aspiring student in her old field.

Marie Stopes was rarely a detached and objective scientific worker. She made careful observations, came to her conclusions, and then believed in them with an almost passionate fervour. In her later years she became renowned for saying what she felt; but she also had the much rarer quality of really feeling what she said. She would not rest contented until she had persuaded dissentients, and always enjoyed the controversy without which any science, even geology, can be a dull thing. One of her last appearances at a scientific meeting was at the Linnaean Society, when she rose to defend one of her long-cherished ideas on the origin of fusain in coal. She spoke with an enthusiasm and vigour which belied her age as much as did her manner and bearing. In her death, British palaeobotany has lost an outstanding figure, and certainly one of its most remarkable and colourful personalities.

She joined the Association in 1911 and was elected an Honorary Member in 1946. W.G.C.

HENRY JOHN WILSON, born at Greenwich on 27 March 1880, died 25 July 1958. He became a member of the Geologists' Association in 1924, of the Prehistoric Society in 1935, and of the Croydon Natural History and Scientific Society in 1936. He was a talented water-colour painter of the Wapping Group, and had also an enviable knowledge of botany, which allowed him to name and even explain the weeds and plants encountered in our excursions.

He told me that while serving in Palestine during the 1914–18 war he would collect palaeoliths, which of course he had to discard. But it was this same interest which brought him to Barnfield Pit, Swanscombe (1934–5), and from our meeting developed a long-lasting friendship. He preferred working the Lower Gravels collecting Clactonian artifacts. During the second world war he would accompany Mr. A. S. Kennard who was working on the Barnfield mollusca and who collected the animal remains saved for him by the workmen.

Wilson was a quiet, modest, kindly, genial and unassuming worker. I am not aware that he published any account of his finds, but undoubtedly he found some outlet for self-expression through his paint-brush. His gift to me of a water-colour of Barnfield Pit (1934–5) is a completely satisfying remembrance of our long association. A.M.

JOHN CARRUTHERS died in Ellerbeck Hospital, Workington, on 10 October 1957, at the age of seventy-six.

He was educated at Holy Trinity Church of England School, Whitehaven, and at Bede College, Durham. His career as a schoolmaster was spent almost entirely in the Whitehaven district. After a short period of teaching in London he joined, in 1901, the staff of the Whitehaven County Secondary School, later to be known as the Whitehaven Grammar School, and after the 1914–18 war he became Geography Master there and continued in that capacity until his retirement in 1947. He served in the Royal Navy from 1916 to 1919.

He joined the Geologists' Association in 1924 and became a Fellow of the Geological Society in 1946. His geological interests were broad, and stemmed in the first instance from his love of the Lake District where, in his younger days, he enjoyed the pleasures of rock-climbing. Later he became particularly interested in geomorphology and in glaciology. During the late 1920s and in the '30s he was a frequent attender of the long Summer Field Meetings of the Association and he will be remembered by many of the older members who regularly took part in the summer excursions.

F.M.T.

By the death of THOMAS WILLIAM MARSH in the Lewisham rail disaster of December 1957 the Association lost a member of thirty-five years' standing, and one who had been consistently active in its affairs. A civil engineer by profession Marsh was particularly interested in problems of coast erosion and the mechanics of superficial earth movements. But the pursuit of geological studies more generally had been his lifelong pastime. He attended many of the Association's meetings, both indoors and in the field. His paper on 'The Alongshore Drifting of Beach Material' (*Proc. Geol. Ass., Lond.*, **36**, 1925), incorporating a considerable body of Marsh's own observations and those of other workers, was a notable contribution to coastal studies.

Born in Canterbury in 1899, Tom Marsh was one of two children of a schoolmaster who was greatly interested in natural history. The family later moved to Rochester where, at the Sir Joseph Williamson's Mathematical School, the son received his early education. In 1916 Marsh went on to study engineering at the City and Guilds Technical College, Finsbury, his course being interrupted by two years' service in the Royal Flying Corps (later R.A.F.). In 1921 he graduated B.Sc. (Engineering) with honours. At his college he was a pupil of J. J. Hartley, whose teaching largely inspired Marsh's interest in geology.

In 1921 Marsh became a pupil of the consulting engineer Oscar Faber, under whom he began to specialise in reinforced concrete construction. Much of his later professional work was in this branch of engineering. He worked in turn for several of the great contracting firms, sometimes on large engineering projects in this country and abroad but also to a large extent on steel and concrete building construction in London and the provinces. In all these works his own part was chiefly in the design office, so he was never for any long period away from London. The staffs of the firms he served held him in high esteem, particularly the younger men, who regularly sought his advice and drew upon his abundant knowledge and experience. He was an associate member of the Institution of Civil Engineers. As a student member of that body in 1924 he won the Miller Prize for an essay on shingle drifting.

For many years Marsh taught structural engineering to evening classes at the Westminster Technical College, and from 1949 until the time of his death taught also engineering geology there. The latter became his favourite teaching subject and he did much to widen the interest of his students. Through his influence several young engineers became members of the Association. He initiated geological field excursions for his classes and had a great liking for visits to the sites of landslips, such as those at Folkestone Warren and Herne Bay.

Tom Marsh took all his work and pastimes very seriously. In public and with strangers he was reserved, but he had a most friendly manner, an unfailing humour and a boy-like enthusiasm which made him at all times a delightful companion. His second wife survives him. Of the two children of his first marriage the daughter, Margaret, is a geologist. G.E.H.

The writer is grateful to the Council for this opportunity of adding to the notice on LEONARD FRANK SPATH which appeared May 1958 (*Proc. Geol. Ass., Lond.*, **69**, 70), especially as he was associated with Dr. Spath during the whole of the latter's career at the British Museum.

Spath was an exceptionally hard worker, seldom leaving his room unless to examine collections in store. He was of a retiring disposition and social functions had little attractions for him. For many years he had not been a frequent visitor to scientific meetings, excepting perhaps the Royal Society to which he was elected a Fellow in 1940, and he was rarely seen at Field Meetings. This reserved manner probably led some to think of him as purely an indoor worker, speculating in the study rather than observing in the field—quite an erroneous impression. He was a really great and discriminating collector and the British Museum collection is enriched by several thousand specimens, mainly ammonites, collected from numerous localities during his vacations, which he always devoted to the cause of Palaeontology.

Early in his career Spath took part in expeditions to Tunisia (1912) (*Quart. J. geol. Soc. Lond.*, **69,** 1913) and to Newfoundland (1919). Apart from a visit to the Jurassic of the Deux Sèvres district of France his foreign collecting was restricted to these two expeditions.

Spath studied the Liassic rocks in Skye and Pabay and published three short papers on them in the *Geological Magazine* (1922, 1923). Numerous other English localities came under his investigation and it is doubtful if there was any known Gault exposure in England which he did not examine. His monograph on the Ammonites of the Gault, published by the Palaeontographical Society (1923–43), was made possible only by his collecting, bed by bed, over many successive years, at Folkestone. His investigation of the Gault was the first serious attempt of any worker to elucidate Gault stratigraphy since the early days of Price. He served on the Association's Council from 1922–4.

He also investigated the Speeton clay of Yorkshire in detail and published a description of the beds in the *Geological Magazine* (1924).

Although many of his visits were made to assist him in problems which arose in connection with the particular investigation that he was engaged upon, he was constantly examining sections solely for the purpose of satisfying his enquiring mind. Few ever knew of this tremendous activity on his part or of the numerous Mesozoic exposures with which he was fully conversant.

He frequently took his Birkbeck College students to Aylesbury and to the Dorset area. He had already begun to study the Upper Jurassic of the Swanage region in detail, and had his health been better in later years, he would undoubtedly have finished this work and published the result of his findings.

Spath's knowledge of world literature was profound as can be seen from works on material from other lands. In all his major works his correlations, and his treatment of comparisons with ammonite faunas of other localities, are masterly and of great value. Many facts of importance concerning the

Jurassic of Britain can be found in his monumental work on Kachh (Cutch) (*Palaeont. indica*, 1927–33). Few other writers have given such comprehensive reviews as was Spath's custom.

His researches were not confined to ammonites of any one system; he was equally an authority on Cretaceous, Jurassic and Triassic ammonites, and he had a thorough knowledge of their Palaeozoic predecessors.

He had an almost uncanny skill in developing ammonites and in exposing and depicting sutures, which he invariably drew freehand.

Spath was a most likeable man, never impatient or irritable, but sometimes depressed and loath to converse. He was much loved by his family, whose illnesses, and especially his wife's death in 1942, must have saddened him greatly. He had very poor health himself during the last years of his life, when failing eyesight necessitated frequent visits to the Eye Hospital. This was a great blow to him but, nevertheless, he remained extremely philosophical and bore all his misfortunes with fortitude. By his death the science of Palaeontology lost a brilliant advocate.

A comprehensive Obituary, with literature, is given in *Biographical Memoirs of Fellows of the Royal Society*, Vol. 3, 1957. A.R.

Mineral Exploration

by DAVID WILLIAMS

Presidential Address delivered 6 *March* 1959

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ABSTRACT: Rapid advances have been made during the past quarter century in field techniques of prospecting for ore bodies, particularly in geochemical and geophysical methods, and also in the application of geological photo-interpretation and laboratory studies to the search for minerals. A conspectus of current techniques warrants progressive confidence in the outcome of future exploration for concealed mineral deposits.

1. INTRODUCTION

IT SEEMS APPROPRIATE that a Centenary President interested in the search for minerals should take this opportunity of reviewing a century's progress in the techniques of mineral exploration and of predicting some future trends in the practice of prospecting. Although it is not surprising that the subject of mineral exploration has received but scant attention in our PROCEEDINGS, it is indeed both remarkable and deplorable that its study has been so sadly neglected in this country, to the detriment of progress in the science and of mineral discovery in the Commonwealth and elsewhere.

Probably most of the world's present mineral production is being won from deposits found at the surface during the half century before the 1914–18 war. Since then the rate of discoveries outside the U.S.S.R. has declined, apart from the spate of uranium finds arising from an unprecedented boom in prospecting after the recent World War. Many outcropping mineral deposits still remain to be found in unexplored regions of the globe, notably in arctic and sub-arctic lands and in tropical jungles, but the chances of making such comparatively easy discoveries become smaller each year. Indeed, the finding of new deposits, mostly concealed beneath a thick mantle of overburden, is becoming ever more difficult without recourse to scientific prospecting based on imaginative geological reasoning, aided by aerial photography and modern techniques of geochemical and geophysical exploration.

Chance has hitherto played a prominent part in the discovery of mineral deposits. Specks of gold fortuitously exposed in the tail-race of a saw-mill led to the gold rush to California in 1849, and the finding of a bright stone by a child playing alongside the Orange River in 1867 heralded the first diamond rush to South Africa. The providential exposure of metallic minerals during the building of railways in Ontario attracted prospectors to the nickel field of Sudbury and the silver veins of Cobalt, and the great vanadium deposits of Minasragra in Peru were accidentally discovered by a herdsman in the high Andes who mistakenly thought he had found fuel for his camp-fire. Drilling for water has been a lucky means of locating buried ore bodies, including base metal deposits in Oklahoma and anhydrite at Billingham in Co. Durham, while the boring for oil near Whitby in Yorkshire led to the discovery of thick potash beds at a depth of 4000 feet. The important bauxite industry of Jamaica was adventitiously foreshadowed in 1942 by the analysis of a red infertile soil, submitted to the Government Department of Agriculture, which proved to be attractively rich in alumina and poor in silica.

These few examples, from the multitude which could be cited, serve to illustrate the conspicuous role played by chance in the history of mineral discoveries. Almost on a par with them are finds due to the guidance of natives, such as those in Central Africa who led prospectors to the rich uranium veins of Shinkolobwe in the Belgian Congo and to several of the Northern Rhodesian copper deposits.

2. TRADITIONAL AND NOVEL METHODS OF PROSPECTING

The indomitable old-time prospector with his pick and shovel, hammer and pan, roamed the lonely places of the earth in search of his El Dorado, lured on by a fortune at the rainbow's end. Scores of mining districts, including the goldfields of the Witwatersrand in South Africa, and many of the great copper deposits of Western America, owe their beginning to his perseverance and his 'nose for ore'. Among the more obvious clues he sought were the rusty 'iron hats' or gossans marking the weathered outcrops of mineralised lodes, sometimes coloured by the vivid blues and greens of oxidised copper minerals, the sooty black stains of manganese, or the pink and green 'blooms' of cobalt and nickel. After finding such conspicuous signs of mineralisation he explored the ground by pitting, trenching or stripping the overburden. Nowadays, if the soil cover is more than a few feet deep and the terrain is suitable for its disposal, a bulldozer or trench-digging machine may be used for removing overburden. In hilly or mountainous country where an adequate supply of water is available at a higher elevation than the ground to be stripped, the time-honoured method of 'booming' or 'hushing', formerly much practised in the north of England when searching for lead-zinc veins, is often effective. Water is impounded at a high level and then released rapidly so as to scour the soil cover from the hill-side. This is analogous to 'hydraulicking', whereby the rock surface is laid bare by powerful jets of water, a technique which met with spectacular success at Cobalt, Ontario, in the early 1900s, by exposing many rich silver veins, and latterly also at Pinchi Lake in British Columbia by disclosing mercury ores beneath a drift cover.

(a) Leached Outcrops: Surface Subsidences

Although the finding of an oxidised capping or gossan consisting of a cellular mass of limonite and gangue may herald the discovery of an underlying ore deposit, such an outcrop often represents merely the oxidised roots of a vanished lode or the surface expression of unprofitable veins. Wide experience and geological acumen are required to interpret the proper significance of the colour variations, texture, structure and extent of such leached cappings in terms of what lies below them. Although a few old-time prospectors had sensed the difference between limonites derived from worthless pyrite and from copper-bearing sulphides, it was not until the studies of Locke and his associates (Blanchard, 1928) were published in the 1920s that the value of leached outcrop investigations in delimiting exploration targets and in estimating the nature and tenor of the underlying ore was generally appreciated. They demonstrated, by careful field correlation between limonite and its contiguous parent sulphide, that the iron oxide derived from any particular sulphide is apt to differ in colour, cellular structure, pulverulency and other physical characteristics from limonite inherited from other sulphide minerals. Their descriptive criteria for the recognition of limonite derivatives diagnostic of specific parent minerals have often been applied successfully in the search for ore, but they must be used with discretion and they are certainly not infallible guides. My own experience in many parts of the world of gossans overlying cupreous ore convinces me that the traits of limonite after each individual copper-bearing sulphide should be locally established by tracing gradations into the parent mineral, for the colour and structure of the iron oxides are prone to vary with the nature of the country rocks. Nevertheless, once the characteristics of the various limonites have been correlated with the original ore minerals and their setting they may then provide valuable clues to exploration elsewhere under similar geological conditions.

The oxidation of massive sulphide deposits is almost invariably accompanied by volume shrinkage and collapse of the gossan, so that in areas where such ore bodies are oxidised underground the surface may display signs of subsidence and crackling which constitute promising guides in the search for buried deposits. For example, in Bisbee, Arizona, the oxidation of massive cupriferous pyrites deposits in limestone at a depth of 700 feet underground resulted in the development of collapse breccias together with peripheral calcite-cemented subsidence cracks which extend upwards to the surface and thus reflect the position of the concealed ore bodies. In consequence, within that district the ground beneath surface subsidences merits close investigation.

(b) Float and Panning

One of the most useful and long-established methods of exploration is the search for 'float', consisting of loose fragments or boulders derived from the weathered outcrop of a mineral deposit, which may be traced back to its source. This technique is especially helpful in glaciated areas such as Canada and Fennoscandia; indeed, it is claimed that the discovery of most of the known ore bodies in Finland which were covered by drift and peat bogs, including the great Outokumpu copper deposit, was essentially due to the tracing of glacial ore-boulder trains back to their source. Clearly the most effective use of this method of prospecting, which is nowadays usually supplemented by geochemical and geophysical surveys, requires a proper appreciation of the nature of glacial erosion and transport.

From time immemorial men have panned stream gravels in search of precious metals and gem-stones, and the finding of rich alluvial, placer deposits has led to many famous rushes. To locate the source of the valuable minerals the prospector works upstream until they fail to show in the pan. Haply he may find thereabouts a few pieces of float, and by trenching ('costeaning') he may then discover the 'mother lode' and test its extension by probing with a sounding bar, earth auger or post-hole digger. The recent discovery of diamond pipes in Yakutia, Siberia, was due primarily to the intensive application of this traditional method of alluvial prospecting; in this case pyrope garnet, an abundant *sputnik* or fellow-traveller of the diamond, was used as a pathfinder mineral in the stream gravels to guide the prospectors back to the kimberlite pipes, the original home of the diamonds.

(c) Metallogenetic Provinces

It has long been recognised that certain regions of the world, known as metallogenetic provinces, are characterised by the relative abundance of particular metals or groups of metals. Within these provinces the rocks and ore deposits, irrespective of their age, may be enriched in the same suite of elements. For example, in the thorium-rich province of the Dutch East Indies, Carboniferous and Tertiary granites, together with their respective derived sediments of Triassic and Recent age, all contain abnormal amounts of allanite and monazite (Davidson, 1951). In Arizona, copper metallisation took place repeatedly between Pre-Cambrian and Tertiary times, and in the plateau country of Colorado, Utah and New Mexico, uranium deposits were formed during the Triassic, Jurassic and Tertiary periods. Other metallogenetic provinces that have been recognised, largely on the basis of production statistics, include the copper belts of Rhodesia–Katanga and Chile–Peru, the goldfields of South Africa and the Canadian shield, and the pyritic zone of southern Spain and Portugal. Acting on the maxim that 'if you are looking for elephants, go to elephant country', prospectors in search of a particular metal or mineral have commonly chosen an appropriate metallogenetic province as a regional guide to exploration. In many parts of the world, however, no such clue is yet available. Fortunately there is now a distinct hope that under favourable conditions it may be possible to select promising areas by carrying out trace analysis on a few samples of igneous rocks or minerals.

Thus, Ahrens & Liebenberg (1950) have demonstrated that the mica of pegmatites near stanniferous veins in South-West Africa is very much richer in tin than the micas of pegmatites in areas devoid of cassiterite deposits. In consequence they suggest that rapid spectrochemical analyses of the tin content of pegmatitic micas might be helpful in deciding whether or not a granite-pegmatite area should be closely prospected for tin. Goloubinoff (1937) reported that a suite of igneous rocks, including diabase, norite and pegmatite, collected from auriferous districts contain eight to twenty-five times as much gold as corresponding rocks in barren areas, and J. H. L. Vogt (1923) recorded a similar enrichment in the nickel content of ferromagnesian minerals in basic igneous rocks containing nickeliferous pyrrhotite ores. In future, therefore, it is likely that increasing attention will be given to the determination of trace element assemblages in specific minerals and rocks as a preliminary means of assessing the economic mineral potentialities of different regions.

(d) Igneous and Stratigraphical Guides

Much exploration has been directed by the knowledge that certain kinds of mineralisation are commonly associated with particular types of igneous rock. For example, tin, tungsten and molybdenum ores are usually intimately related to acid intrusive bodies, titaniferous magnetite and ilmenite to gabbro-anorthosite, niobium and apatite to alkaline syenites and carbonatites, and chromium and platinum to ultrabasic intrusives. Such associations provide a broad guide to prospecting, as does the propensity for ore in certain districts to occur within or near apically truncated acid-intermediate igneous stocks.

In the case of syngenetic sedimentary deposits, such as bedded ironstones, evaporites and phosphates, the problem of ore discovery is a comparatively simple matter of determining the stratigraphical sequence and structure of the strata in order to predict where the valuable horizons may be encountered at any given place. Similarly, in pseudo-stratified basic intrusives, such as the Bushveld Complex of South Africa, chromite, platinum, magnetite and ilmenite are each concentrated in distinctive layers at successively higher horizons within the highly differentiated basic body, so that the task of locating particular types of ore is considerably simplified. Moreover, in the case of the chromite layers, high-chromium varieties occur at low horizons in the Complex in magnesia-rich dunites and serpentines, whereas high-iron chromites are associated with pyroxene-rich peridotites at higher levels, as might be predicted from the fact that Cr^3 and Mg^2 ions are respectively smaller than Fe^3 and Fe^2 ions and are therefore likely to be concentrated in the early crystals of chromite. As more information is gleaned about the chemical and environmental conditions leading to the formation of sedimentary ores, and about the processes of differentiation conducive to the segregation of syngenetic deposits within igneous rocks, the basis of exploration for these ores will become more firmly established.

Concealed epigenetic mineral deposits, formed by cavity filling or the replacement of pre-existing rocks, are usually more difficult to find than syngenetic ores, for their systematic discovery commonly entails detailed structural mapping and an appreciation of the reason why particular host rocks are favourable ore loci. Hitherto the approach to this problem has been largely empirical, the search for ore in individual districts being initially concentrated on sedimentary formations, lava flows, igneous intrusions or metamorphic rocks known by experience to be hospitable, and on structural settings analogous to those already proved to be propitious for ore deposition. Thus, if in a certain area ore deposits are known to have replaced a particular limestone horizon beneath a shale parting in the fractured crest of an anticline, then a similar combination of lithology and structure in nearby ground clearly merits thorough investigation. This rule-of-thumb method of exploration has been applied successfully for generations past in district after district even though the real reasons for ore deposition still remain a mystery. It is realised in many cases that the host rocks have been hospitable by virtue of their primary or secondarily induced permeability to the passage of ore fluids, or because of their ready chemical reactivity. Much more field and laboratory research must be done, however, before it becomes possible to predict with reasonable assurance whether or not certain formations in particular geological environments are likely to harbour epigenetic mineral deposits.

(e) Structural Control of Ore Deposition

Although it was recorded more than a century ago (Leithart, 1838) that veins above the Whin Sill in the north of England steepen and widen when crossing sandstones and limestones, the first detailed application of structural geology to problems of mineral exploration probably dates back to about 1900 when the Anaconda Mining Co. established a resident geological staff to maintain a close study of the complex vein systems at Butte, Montana. Since then mining geologists have increasingly stressed the importance of meticulous surface and underground mapping around known mineral deposits as a means of determining the structural controls of ore localisation. Once these are truly recognised the search for nearby ore bodies and those in analogous structural and lithological settings becomes more pointed. Actuated by this method of approach much fruitful exploration for epigenetic deposits has been carried out on favourable structures within propitious host rocks. Indeed, the voluminous literature which has accumulated during the past half century on structural features associated with these deposits reflects the emphasis placed by mining geologists on the paramount role of structure in determining the final locus of ore deposition.

In many mining fields the fundamental structural control of ore shoot localisation is the fracture pattern, and an understanding of its origin and behaviour provides a valuable clue to the disposition of vein deposits and accompanying replacement ore bodies. Not only do fractures afford channelways for the passage of ore fluids but they also constitute sites for the precipitation of minerals and starting-places for pervasive replacement of the wall-rocks. Attempts to predict the location of ore shoots along fractures must take into account the fact that fissure veins tend to be more productive within relatively competent rocks, that tangential movement along the walls of an irregular fracture may create propitious openings for infilling by ore minerals, and that enrichment is more likely than not to occur at vein intersections. Moreover, the effects of folds, pre-existing breaks, igneous contacts, bedding and cleavage planes on the behaviour of fractures must be given due consideration when efforts are being made to locate shoots along their courses. Once the characteristic pattern of known fissure veins in a district has been established, further exploration is simplified even though the actual cause of the fracturing may remain in doubt. Orderly vein patterns vary from a simple series of parallel or nearly parallel veins each containing a similar kind of ore, to a complex system marked by three or more dominant trends each characterised by a distinctive suite of ore minerals. For example, in central Cornwall a parallel conjugate system of veins trending ENE., carrying mainly tin, tungsten, arsenic and copper, is cut and heaved by a later set of N.–S. cross-courses bearing zinc, lead, antimony, uranium, barite and other comparatively low-temperature minerals.

Attempts to explain the observed orientation of shear and tension fractures have mainly invoked the concepts of rock failure elaborated by Becker, the ‘Wisconsin School’, E. M. Anderson and Griggs, though they have often overlooked the fact that the same stress orientation may result from quite different types of loading. Nevertheless, the arrangement of fractures in many districts, particularly where the rocks are almost homogeneous, conforms closely to the ideal theoretical pattern consisting of two sets of complementary shears and a set of tension cracks aligned so as to bisect the acute angle between the shears. But where the homogeneity of the country rocks is destroyed by the presence of bedding planes, cleavage, schistosity, pre-existing fissures, and formations of different competency the ensuing fracture pattern may depart widely from the ideal arrangement. The concept of the strain ellipsoid has often been profitably applied in exploring for vein deposits even though its serious limitations have frequently been ignored.

Indeed there is still a great need for more experimental and theoretical research on the mechanics of rock deformation and failure in order to achieve a proper understanding of how rocks are deformed on a local and regional scale within various geological frameworks and structural environments.

Experience has long since shown that the contacts between rocks of different competency are prone to be zones of weakness and fracturing suitable for ore deposition. As this is especially so along the margins of igneous intrusions it is not surprising that prospectors have always paid particular attention to the vicinity of these contacts, irrespective of whether or not the ore is genetically related to the igneous bodies.

In many productive districts there is a close spatial relationship between the disposition of ore deposits and the arrangement of fold axes, anticlinal crests, synclinal troughs, the limbs of folds or the plunge of drag folds. Where the ore was in existence before the onset of folding it is deformed with the enclosing rock, and its discovery, especially in the case of syngenetic deposits, may involve no more than the elucidation of a simple structural problem. In areas where such bedded deposits have been intensely deformed, as in the base-metal sulphide bodies of Rammelsberg in Germany, the ore shoots may be considerably thickened along the flexures due to flowage of the softer ore minerals from the attenuated limbs of the folds. Where ore has been introduced into rocks already folded it may be localised in domal or anticlinal structures by virtue of cavity filling or the selective replacement of favourable horizons, or by the channelising of solutions parallel to the axes of plunging drag folds. Dilatational openings in zones of cross folding, or fractures formed later than the folding may also be favourable sites for ore deposition. In a great many cases the precipitation of ore in folded rocks has been strongly influenced by the blanketing effect of a semi-permeable horizon beneath which the ore fluids ascended towards anticlinal crests.

The hunt for ore bodies displaced by faults is, of course, part and parcel of the routine work of a mining geologist. Its successful accomplishment may involve detailed mapping of the local structure and stratigraphy, coupled with an ability to visualise geology in three dimensions and to recognise whether the displacement is pre-ore or post-ore in age. Thorough training in structural geology obviously adds enormously to the competence of those engaged in mineral exploration, not only in searching for dislocated segments of ore bodies but also in prospecting over virgin territory.

On a broad regional scale, folding, faulting, igneous activity and related hypogene mineralisation in orogenic belts tend to follow a well-recognised sequence of events, and in many parts of the world the disposition of ore bodies is related to lineaments such as fold belts, zones of faulting or shearing, rift valleys, and aligned intrusions. The Mother Lode in California and the auriferous Kirkland Lake 'break' in eastern Canada are both located in zones of folding and reverse faulting each stretching for a distance of 150 miles, while the Great Dyke of Southern Rhodesia and its associated mineral deposits extend along a belt 300 miles in length aimed at the heart of the Bushveld Complex. Billingsley & Locke (1941) have noted the occurrence of many deposits in the western United States where orogenic belts are intersected by later elements such as transcurrent faults, and they have suggested that heat and fluids, including the ore-forming fluids, are most likely to rise at or near intersections of major structures where the crust is fractured or weakened to great depth.

Quite recently Mayo (1958) has investigated the structural framework of the south-western United States for evidence of four main trends of lineament tectonics, aligned NW., NE., N.–S. and E.–W., and has observed a systematic relationship between the intersection of certain elements of the regional framework and the positions of known mining districts. Wisser (1959), in a stimulating and provocative paper, has described several well-defined lineaments in the Cordilleran region of the United States, which are characterised by zones of fracturing, dyke intrusions, alignment of igneous stocks, physiographic features and the presence of numerous ore deposits. He points out that the major lineaments, including most of the faults and geosynclinal axes of the Cordillera, all follow one or more master trends, and suggests that there is a genetic relationship between geosynclinal axes and major crustal fracturing. Moreover, he observes that many great mining districts are located along pronounced crustal flaws which were activated by diastrophism, in some cases repeatedly since Pre-Cambrian times, so that they tapped the deep-seated source of the ore fluids at successive metallogenetic epochs. For example, the NE.-trending Colorado lineament, which originated in Pre-Cambrian times and was reactivated during the late Cretaceous Laramide orogeny, accounts for most of the precious and base-metal production of Colorado, the famous Leadville deposits being situated at its crossing with a Permo-Carboniferous geosynclinal axis striking NW. In addition, two of the greatest mining districts on earth, at Butte and Bingham-Park City, lie at the intersections of lineaments. Brock (1956) has emphasised that 'a broader knowledge of fractures of world importance, of their habits, their pattern and their mathematics, could have a profound bearing on an exploration policy. A study of such fractures . . . is a prelude to the assault on the covered areas.'

Although our understanding of the relationship between lineament tectonics and the sites of mineral deposits is still slight and subject to personal bias, it certainly seems that as geological mapping is extended and more is known about the structural and igneous activity within an extensive region, the more clearly will the correlation emerge. In that event it may become possible to define with reasonable assurance the most promising districts for mineral exploration.

(f) Wall-Rock Alteration

Most ore deposits, particularly those of epigenetic origin, are surrounded by zones of alteration in which chemical and mineralogical changes have been induced, usually during the period of ore formation. These zones form target rings or haloes around the ore bodies, each successive ring being ideally characterised by a diagnostic suite of minerals or type of altered rock. Since the alteration haloes are usually more extensive than the ore body itself their recognition may greatly facilitate the task of mineral exploration, though to be of practical value as guides to ore they should be neither too narrow nor so widespread that they merely indicate the possible presence of ore within a large tract of country. In some cases the mineralogical features of the altered rocks may be so distinctive and conspicuous as to be readily discerned in the field, whereas in others the changes may be so subtle as to be decipherable only by careful microscopical examination or by chemical, X-ray or differential thermal analysis.

Altered wall-rocks alongside deep-seated, hypothermal deposits may contain garnets, pyroxenes, amphiboles, tourmaline, biotite and albite; those adjacent to mesothermal ore bodies are often extensively sericitised and chloritised, while those associated with the shallower, epithermal deposits may be characterised by the abundant development of carbonates, adularia, chalcedony, alunite and chlorite, and those close to replacement deposits in limestone may be dolomitised, silicified or contain a profusion of skarn silicates. Moreover, the individual minerals are often more or less concentrated around the ore bodies in successive zones, the systematic mapping of which may be helpful in the search for ore. Thus, in Cornwall the tin lodes in granite are frequently surrounded by successive shells rich in tourmaline, chlorite, sericite and kaolinite; at Butte, Montana, the alteration aureole alongside many of the veins in monzonite is distinguished by an innermost narrow selvage of silicification followed outwards by zones rich in sericite, then kaolinite and finally montmorillonite; and at Rio Tinto, Spain, the porphyry alongside the massive pyritic deposits may be intensely sericitised or chloritised for more than 100 metres from the footwalls of the ore bodies. Schwartz (1955) has given an excellent review of the more important contributions published during the present century on the subject of hydrothermal wall-rock alteration and its application to mineral exploration.

With the advent into the geological field of the mass spectrometer a novel and promising approach to prospecting has recently emerged, for a study of the non-radiogenic isotope ratios of certain elements may throw light on the origin of mineral deposits and indicate zones of hydrothermal activity around ore bodies. Thus, the ratio of O^{16}/O^{18} is extremely temperature-sensitive in the lower ranges, the amount of O^{18} incorporated in minerals being slightly greater at low than at high temperatures. Engel and his co-workers (1956) have demonstrated that in the Leadville limestone in Colorado the oxygen isotope ratios in quartz and carbonates in the extensive dolomite aureoles around the lead deposits vary systematically with respect to the position of the ore, the O^{18} content decreasing progressively towards the ore bodies and their feeders. Limestones, dolomites and cherts many miles away from the mineralised areas and unaffected by hydrothermal solutions contain oxygen isotopically approximating that in other unaltered carbonate sediments. Increasingly higher temperatures of formation of the dolomite halo can be depicted by drawing contours of oxygen isotope values, the lines of equal O^{18} content crudely encircling the ore. Isotopic variations are detectable at a distance of several miles from the known ore bodies, even though the structure, texture and trace element assemblages of the minerals and rocks within the dolomite aureole cannot be systematically related to the sites of ore deposition. It seems likely, therefore, that oxygen isotope determinations on specimens from the surface and underground may prove helpful in prospecting for hydrothermal ores, and attempts are now being made to develop a simplified field technique for measuring the oxygen isotope ratios in carbonate rocks.

Cannon and others (1958) have suggested that isotopic analyses of lead from suites of non-radioactive sulphides, such as pyrite and galena, may indicate either regional or local concentrations of uranium and thorium. They have observed a strong tendency for non-radioactive minerals to be enriched in radiogenic lead when they occur within uranium deposits or their wall-rocks, though they have not detected any direct correlation between the grade of ore and the degree of enrichment of radiogenic lead in the non-radioactive minerals. It is claimed that the presence of primary sulphides appreciably enriched in Pb^{206} and Pb^{207} may be enough to disclose the existence of a new uranium district, a new ore body in a known uraniferous area, or a uranium-bearing vein near existing workings. Similarly, sulphides abnormally enriched in Pb^{208} might indicate the possibility of a thorium province. Apparently, therefore, the judicious use of lead isotope analyses may be an empirical aid in exploring for radioactive deposits, though such analyses are still too expensive for routine investigations.

(g) Zonal Arrangement of Ores

Long before Spurr (1907) formulated the zonal theory of ore deposits it had been recognised in some districts, notably in Cornwall and Devon, that the mineral composition of ores changes both downwards and inwards towards the emanative source of the ore solutions. Originally the theory was applied only to the zonal disposition of minerals around a core of parent igneous rock, though nowadays the concept has been extended to include mineral zoning related to sedimentary and metamorphic processes (Park, 1955).

Dewey (1925), in a Presidential Address to our Association, described the classic example in Cornwall of a roughly concentric arrangement of different ore and gangue minerals with respect to the exposed granite cupolas. Here an innermost tin zone, mainly confined to the granite, is overlain by successively higher and more widespread zones carrying tungsten, copper, zinc, lead, silver, antimony and finally iron, the concomitant sequence of gangue minerals being tourmaline, chlorite, fluorite, dolomite, barite and calcite.

In the famous Butte district of Montana a central zone of copper veins containing enargite, bornite and chalcocite is enveloped by an intermediate zone characterised by chalcopyrite, tennantite and some sphalerite, and this in turn is surrounded by a peripheral zone bearing sphalerite, galena and rhodochrosite. Similarly, at Bingham in Utah, copper ores occur within and contiguous to an intrusive stock, copper and lead-zinc farther out, and silver-lead ores still more distant from the igneous contact. In this country, Dunham (1934) has recorded a systematic zonal arrangement of minerals in the North Pennine ore field. Here fluorite is the dominant gangue constituent in the inner zones, barite of the outer, while chalcopyrite occurs near the centres of the inner zones, and galena-sphalerite are mainly concentrated in the outer part of the fluorite and inner part of the barium zone. Where there is a vertical zonal sequence in the North

Pennines it corresponds with the more obvious concentric lateral arrangement. According to geophysical evidence this ore field may be underlain by concealed bodies of granite which are probably genetically related to the mineral deposits.

Although the real causes of mineral zoning have never been satisfactorily explained, it is apparent in many mining districts that as the ore fluids ascended or moved outwards from their source the earliest minerals were deposited at depth whereas the later ones were precipitated closer to the surface.

In deep-seated hypothermal deposits there is usually little or no variation in mineralogical composition of the ore within mineable depths, but in the closely allied pyrometasomatic deposits formed in limestones alongside intrusive stocks an inner zone containing magnetite, hematite and scheelite may be followed outwards by sheaths characterised successively by sulphides of copper, zinc and lead, and perhaps also by a peripheral display of cinnabar. Zoning as a guide to different types of ore may also be helpful in areas containing epithermal, leptothermal or mesothermal deposits formed at shallow to moderate depths, though in epithermal ore bodies the fact that the zones are apt to overlap or be telescoped into a narrow vertical range may militate against their usefulness in guiding exploration. Where the mineralogical changes in depth and laterally are neither too slow nor too rapid, as in many leptothermal-mesothermal deposits such as those of the north of England and Butte, Montana, the search for specific types of ore is greatly facilitated by a knowledge of the zonal distribution of the minerals.

Variation in the mineral content of syngenetic sedimentary deposits may be related to old shore lines, and ore bodies concentrated by metamorphic processes may be zoned according to the mobility of the valuable constituents. Clearly, the proper establishment of zones within any mine or district necessitates an understanding of the vertical and lateral distribution of individual minerals in relation to the rock types, structures and ore bodies. Although this normally implies that a considerable amount of mining has already been accomplished, the prospector in virgin territory must always be alert to the possible existence of hypogene zoning, bearing in mind the published records of its occurrence and nature in many geological settings.

(h) Direction of Flow of Mineralising Solutions

Any information that can be gleaned about the direction of movement of mineralising solutions which deposit ore by cavity filling or replacement may be helpful in the search for epigenetic deposits. Recognition of the direction of flow may indicate the conduits along which the ore fluids travelled, besides shedding light on the distribution of specific metals and minerals throughout the ore bodies. Among the many techniques which have been used to determine the direction of motion of ore solutions are those involving (i) analysis of crystal asymmetry; (ii) estimation of the relative pressure of formation of hydrothermal minerals by measuring the temperature at which their liquid inclusions decrepitate; (iii) establishment of a temperature gradient by observing exsolution textures, determining the iron content of sphalerite, making pyrite geothermometer measurements, and studying the luminescence of certain minerals; (iv) plotting metal-ratio contours across ore bodies which display mineral zoning; (v) location of high radioactive anomalies within igneous intrusions and around their margins; and (vi) determination of stable isotope fractionation in minerals. Only brief reference to each of these techniques can now be given.

Newhouse (1941) and Engel (1948) have described how the asymmetric features of quartz crystals, and their partial encrustations, as seen in vugs and steeply dipping veins, may demonstrate the direction of flow of mineralising solutions. On most of such crystals the smaller rhombohedral faces develop on the upper, lee side of the mineral, whereas the enlarged rhombohedral forms grow on the stoss side, facing the rising solutions. In the case of cubic minerals, such as galena, the direction from whence the nutrient solutions came is indicated by the thicker growth zones and larger faces which develop on the upstream side of the asymmetric crystals. Hosking (1954) has observed encrustations of mica, apatite and bertrandite on the stoss side of large quartz and felspar crystals in the druses of some Cornish pegmatites, and has attributed them to preferential development on the side of the phenocrysts that faced the oncoming solutions. Careful and critical examination of crystal asymmetry, growth banding, overgrowths and analogous criteria may thus contribute towards a satisfactory interpretation of the direction of flow of ore fluids and so help to guide exploration.

A hundred years ago Sorby (1858) described how primary fluid inclusions in a mineral might provide data whereby the temperature of its formation could be calculated. He rightly assumed that under the temperature and pressure conditions prevailing at the time of crystallisation, each cavity was completely filled with a single fluid phase, and that during subsequent cooling the fluid contracted and enclosed a small bubble of gas. Broadly speaking, the higher the temperature of mineral formation the larger is the size of the bubble in relation to that of the whole inclusion. If the inclusions are of regular shape their degree of filling can be accurately estimated under the microscope and the temperature of disappearance of the vapour phase can then be calculated. This temperature can also be determined directly by heating a fragment or thin slice of the mineral on a heating stage and observing the temperature at which the bubble vanishes.

The temperature of filling, when corrected for the estimated pressure at the time of crystallisation, coincides with that at which the inclusion was originally trapped by the growing crystal. Despite the limitations of this visual method of geothermometry it can be used satisfactorily for assessing the approximate temperatures of formation of certain minerals, notably quartz, fluorite and sphalerite, throughout an ore body, and thereby indirectly afford evidence concerning the direction of flow of the mineralising solutions.

The decrepitation method of measuring the degree of filling of liquid inclusions in hydrothermal minerals, first suggested by F. G. Smith (see Scott, 1948), is much more convenient than the heating stage optical method. It entails uniform heating in a furnace of powdered samples of the mineral to be tested (commonly quartz) until the vapour bubbles disappear and the pressure of the liquid in near-surface inclusions causes them to explode in great profusion. The temperature at which the frequency of decrepitation increases abruptly corresponds to a few degrees above the filling temperature and that of mineral formation. Moreover, since the decrepitation temperature is a function of two variables, namely the temperature and the pressure under which the mineral formed, the latter can be calculated if the former is determined. Consequently, if decrepitation tests are carried out on samples of a particular mineral collected from many parts of an ore body it is possible to depict isotherms, isobars and lines perpendicular to them indicating the direction of flow of the ore-bearing solutions. Once the flow picture has been established the basis of subsequent exploration is correspondingly more secure. Furthermore, if it can be demonstrated by decrepitation tests on gangue minerals, such as quartz, that high or low temperature varieties are spatially related to the distribution of high-grade ore, the search for this valuable material is eased.

If it is assumed that the ore-bearing fluids cooled as they travelled away from their source, the direction of flow may be inferred by estimating the relative temperatures of formation of specific minerals from place to place in a deposit. Ingerson (1955) has given an excellent account of various methods of estimating the temperatures of geological processes, and of the value of certain minerals as geological thermometers. Occasionally it is feasible to employ the inversion points of specific minerals as temperature indicators; for example, the high–low inversion of quartz is usually effected at approximately 573° C., the change of hexagonal to orthorhombic chalcocite at 105° C. and the transition from cubic argentite to orthorhombic acanthite takes place at 175° C. Moreover, minerals that form a single homogeneous phase above a known temperature and unmix on cooling to yield exsolution intergrowths serve as geological thermometers by indicating that they crystallised above the temperature of homogenisation. Among the many mineral pairs for which exsolution textures can be used to establish temperature limits are sphalerite-chalcopyrite, which unmix at about 375° C., bornite-tetrahedrite at 275° C., and galena-matildite at 210° C.

Where the composition of mix-crystals is controlled by their temperature of formation, chemical analyses of the crystals provides an indication of their formational temperature. It has long been known that pale-coloured sphalerite, with a low iron content, crystallises at low temperatures, whereas dark, iron-rich varieties form at moderate to high temperatures. Recent work by Kullerud (1953) has established the iron content of sphalerite formed in equilibrium with pyrrhotite at temperatures from 400° C. to 900° C., and the resulting curve has been extrapolated down to 140° C. If there is evidence of an excess of FeS in the solutions from which the sphalerite was formed, as testified by the presence of contemporaneous pyrrhotite, then the iron content of the blende is directly related to the temperature of deposition of the zinc sulphide. Thus, by determining the iron contents of sphalerite samples from various parts of a mineralised zone it may be possible to locate 'hot spots' corresponding to the distribution of iron-rich varieties, the most ferriferous being concentrated towards the entrance channels along which the ore fluids ascended. Indeed, it is claimed that this technique has already been applied successfully in Norway to locate such conduits, a large sulphide deposit being subsequently discovered by drilling aimed at the inferred intersection of convergent channels.

If pyrite is present in an ore body it should be possible, according to Smith (1947), to gain an idea of the temperature of its deposition by using a pyrite geothermometer. This device measures the thermoelectric potential of pyrite against a metal, by touching the mineral simultaneously with a hot and a cold probe and recording the voltage developed between them. The method assumes that more perfect crystals of pyrite, with few lattice discontinuities and excess iron with respect to sulphur, always grow at higher temperatures and have a more negative thermoelectric potential than crystals deposited at low temperature. Although I consider this assumption is open to question on several scores, notably the possible existence within the pyrite of inclusions and lattice impurities, the technique has yielded fairly consistent results in determining the temperature of deposition of pyrite in many deposits, including those of Rio Tinto, Spain, and has thereby provided useful information concerning the direction of flow of the ore solutions.

According to McDougall (1954) several types of luminescent phenomena, including fluorescence and thermoluminescence, are often displayed by particular minerals near the margins of certain intrusive rocks and also close to hydrothermal ore deposits. Fluorescence in minerals is caused by their content of trace element 'activators', while thermoluminescence is mainly due to the effect of radioactive emanations on the crystal lattices of minerals and is readily detected by heating specimens below red heat in a dark room. Since the concentration of trace elements and the distribution of abnormal radioactivity often bear an intimate relationship to intrusive rocks and epigenetic deposits, it is claimed that a knowledge of the spatial arrangement of luminescent minerals may be helpful in locating potential ore zones. For example, the thermoluminescence of carbonates and occasionally of platy minerals, such as chlorite, is conspicuous in the wall-rocks of certain ore bodies in Quebec and sometimes extends outwards from the margins of the deposits for distances of up to forty feet.

Gross (1952), after investigating several intrusive bodies and associated mineral deposits in Canada, contends that stocks and batholiths of igneous or initially sedimentary origin are characterised by zones of higher-than-normal radioactivity in the vicinity of ore structures, whereas such concentrations are lacking in intrusives barren of ore. He thus concludes that an alpha-counting survey of the distribution of radioactive elements can assist the search for ore. Moreover, he claims that the distribution pattern of zirconium, silica and heavy metals can also be applied in much the same way as that of radioactivity. This novel method of locating favourable areas for mineralisation is based on the supposition that late-stage solutions derived from acid-intermediate magmas are relatively rich in radioactive elements and tend to flow towards areas of low pressure along the same structural channelways, including faults and fracture zones, as those traversed by the ore fluids.

Provided enough assays of ore samples are available from different parts of a mineralised zone a statistical analysis of the data may yield evidence of metal or mineral zoning. For instance, if the samples are assayed for lead and zinc, the ratios of these metals can be computed and plotted on plans and sections. It may then transpire that the ratio of lead to zinc diminishes with increasing depth and also laterally towards fault zones which served as ore-solution pathways. Moreover, since the contour lines of equal lead:zinc ratios are often likely to be normal to the direction of flow of the mineralising solutions it may thus be possible to discover the channels along which the ore fluids travelled. Contoured plans depicting various metal ratios may also disclose sympathetic or antipathetic relationships between the distribution of particular metals and thereby facilitate the search for them in unexplored ground.

Reference has already been made, in connection with O^{16}/O^{18} ratios in dolomites around certain lead deposits in Colorado, to the application of isotope studies in mineral exploration. Hitherto the investigation of isotopic fractionation as a means of establishing temperature gradients has been almost entirely confined to compounds of light elements formed at relatively low temperatures. It is hoped that research will soon be extended into the domain of heavier elements, such as copper and zinc, and that an understanding of their isotopic distribution will shed light not only on the direction of movement of ore fluids but also on the genesis of mineral deposits.

(i) Geochronology

A knowledge of the absolute age of rocks is obviously helpful in mineral exploration, for it provides the means for dating periods of folding, faulting, igneous activity and related mineralisation. Among the various methods of age determination now employed, some of dubious value, are those based on uranium:lead, thorium:lead, potassium:argon and rubidium:strontium ratios. Once a certain epoch of syngenetic or epigenetic mineralisation is dated the search for deposits formed at that particular time may be concentrated on rocks not younger than that epoch, If, for example, it can be demonstrated that a certain episode of mineralisation is related to a specific intrusion or stage of batholith emplacement then the dating of that igneous activity can be of assistance by directing exploration for contemporaneous mineral deposits into ground where the rocks are not much younger than that activity. Indeed, the precise dating of metallogenetic epochs promises to play a valuable role in future exploration programmes.

(j) Palaeo-ecology

Ellison (1955) has pointed out that the use of palaeo-ecology as a geological tool in the search for mineral deposits, including coal and oil, is still in its infancy. This science, which is concerned with the inter-relation between organisms of the past, now represented by fossils, and their physical and biological environments, has already proved useful 'in the search for oil and gas in reservoirs controlled by reef masses, strand line sand bodies, and marine-nonmarine intertongues'. In future it is likely to be applied also to prospecting for metals and non-metals. Ellison states that 'the most important economic use of environment studies is to interpret the geography of a particular group of strata that contain valuable earth materials or which act as hosts to oil and gas accumulations or ore deposits. Reconstruction of the palaeogeography gives clues to the presence or absence of strata containing the economic materials. It gives clues on where to predict other valuable strata, and thus guides exploration activities.' Such studies could be applied with advantage to the search for various types of sedimentary ironstone, including those formed in environments favourable to the growth of organisms capable of precipitating iron. Indeed, in exploring for all sorts of metalliferous and non-metalliferous deposits enclosed within sedimentary formations, an appreciation of the palaeogeographic distribution of the sediments and the environmental conditions under which they were laid down would provide a key to exploration.

Copper, lead and zinc deposits commonly occur in limestones whose porosity, permeability and chemical properties are largely dependent on conditions of sedimentation, so that a knowledge of the palaeogeographic distribution of favourable limestones affords a clue in the pursuit of ore. Ohle & Brown (1954) have shown how the presence or absence of algal reef masses (rolls) in Cambrian limestones in Missouri has influenced the emplacement of lead ore bodies. Apparently the permeable algal reef structures provided propitious passageways for ore solutions, the trend of the reef masses being related to the depth and contour of the Cambrian seas. They claim that reconstruction of the palaeo-ecological conditions and especially the palaeogeography would yield clues for future exploration.

Again, since marine phosphate deposits are commonly formed near the edge of the continental shelf, knowledge of the migration of the shelf during geological time, depicted on palaeogeographical maps, would assist in the discovery of such deposits.

The growing realisation that palaeo-ecological factors may play a significant and often a dominant role in determining the localisation of many kinds of mineral deposits augurs well for future discoveries.

3. AERIAL PHOTOGRAPHY

The introduction of aerial photographs has been an enormous boon to the prospector by providing him with base maps on which to plot field observations, by revealing a wealth of structural detail, by affording a bird's-eye view which facilitates the planning of exploration programmes, and by expediting the geological interpretation of undeveloped areas. In regions not too densely masked by vegetation and where rock outcrops are plentiful the structures are revealed so clearly on the photographs that geological maps may virtually be compiled in the office if a pedestrian reconnaissance has previously been made. Even in forested areas the nature and pattern of the vegetation, the topographical relief and the drainage pattern, as displayed on the photographs, provide valuable aids to geological interpretation. In the Belgian Congo–Rhodesian copper belt the vegetation over limestone is so different from that over shales and schists that aerial photographs clearly indicate geological formations buried beneath some fifty feet of deeply weathered overburden.

The type of aerial photographs most commonly used by geologists are vertical ones at scales varying between 1:60,000 to 1:10,000, depending on the size of the area and the amount of detail required. Each photograph, about nine by nine inches in size, overlaps its neighbour by roughly 60 per cent so that when the pictures are examined stereoscopically the ground appears in relief and simulates a relief model. Geological interpretation of the photographs entails an assessment of the significance of various types of topography, drainage patterns, linear features, vegetation and soil cover, all of which reflect in some degree the nature and structure of the underlying rocks. In order to accentuate particular features of the geology or vegetation the photographs may be taken in colour or with appropriate types of emulsions and filters.

Air-photo mosaics on the smaller scales enable the geologist to make rapid studies of extensive areas, paying particular attention to major structural features, fracture patterns and lineaments, many of which may escape detection on the ground. Although every field geologist should be capable of interpreting photographs of his area to a considerable degree, a specialist photo-geologist of wide experience is likely to extract more information from the pictures and his help should never be neglected. For detailed surface geological mapping, larger-scale photographs are required so that the field geologist can record his observations on transparent overlays in register with the photographs. After these observations have been plotted it is usually possible to relate particular sedimentary formations or igneous rock types to the morphology, textural pattern or tonal variations as displayed on the pictures. Mapping can then be extended with reasonable assurance into neighbouring unvisited territory. For prospecting purposes the photographs may be of immediate service by revealing quartz veins, gossans and unusual colours related to mineralisation, in addition to fold structures, joints and fracture patterns of possible significance in ore localisation.

Willox (1958) states that when geological maps produced by photo-interpretation are compared with those based on field mapping alone, the most striking feature is the large amount of additional structural detail revealed by the 'photogeological' map, even though the area may be masked by a considerable cover of soil or vegetation. On the other hand some lithological variations may be detected on aerial photographs only if the rock types weather in different fashion or support dissimilar kinds of vegetation, though this drawback may be partly overcome by using colour photographs. Clearly the best practice is a judicious combination of photo-interpretative methods and geological field mapping.

Any exploration project should begin, if possible, with a careful examination of available aerial photographs. Their interpretation is obviously simplified and likely to be more accurate if geological sketch-maps or field traverse observations are already in existence, but it may be necessary or even desirable to complete a preliminary photo-interpretation before planning ground traverses and visits to critical areas disclosed by the photographs. Much time and expense can thus be saved in an exploration programme by reducing the amount of detailed geological mapping and traversing on the ground.

Enormous areas of the Pre-Cambrian Canadian Shield around the Great Lakes have recently been mapped during 'Operation Overthrust' on mile-to-the-inch photographic mosaics, using colour photographs in specially selected areas. Over an area of some 400,000 square miles all the known geology has been compiled and supplemented by geological photo-interpretation, so that detailed field work can now be concentrated on the most promising districts. In addition the Operation has provided an admirable basis on which to plan geophysical and geochemical surveys and to interpret their results.

As an indication of the speed of carrying out regional geological mapping and interpreting the data, Willox (1958) cites the example of a combined photo-interpretation and field survey of 34,000 square miles in Tanganyika at a scale of 1:50,000, which was completed in eighteen months by a team of seven geologists. The need for aerial photography in mineral exploration is thus emphasised by the demand for speed, economy and efficient geological mapping, particularly in undeveloped areas, for detailed structural information, and for its integration with geophysical and geochemical techniques of prospecting.

4. GEOPHYSICAL PROSPECTING

During the past thirty-five years geophysical prospecting has achieved many spectacular successes, especially in oil-field exploration, and it is now widely used in the quest for other kinds of concealed mineral deposits. The essential requirement in all branches of geophysical prospecting is that there should be an appreciable difference in certain physical properties of the mineral deposits and their enclosing rocks, or between adjacent geological formations when structural problems are being investigated. Seldom can the methods reveal directly the presence or exact nature of an ore body. The principal techniques used in prospecting for minerals other than oil are the magnetic, gravimetric, electrical and radiometric, by means of which it may be possible respectively to indicate the occurrence of magnetic bodies, relatively light and heavy rocks, conductive zones and radioactive deposits.

The use of a geophysical method of mineral prospecting dates back to the beginning of the seventeenth century, when a primitive magnetic sun-dial compass was employed in Sweden to locate iron ore bodies. Nowadays ground magnetic surveys utilise a dip needle or more refined magnetometers to detect the distribution of magnetite-bearing and other magnetic rocks. These instruments are capable of detecting deeply buried deposits of magnetic iron ore and bodies of pyrrhotite possibly containing copper and nickel, besides being helpful in tracing concealed contacts between sedimentary rocks, lavas and intrusive masses. It must suffice to mention but one example of the indirect use of the magnetic method, namely its application in the Witwatersrand of South Africa to the location of a gold-bearing conglomerate, known as the Main Reef, beneath a thick unconformable cover of younger sediments. Although the reef itself is virtually non-magnetic its approximate concealed position can be obtained by locating a magnetic shale horizon of conformable attitude a known distance stratigraphically below the auriferous conglomerate. The magnetometer fixes the position of the sub-outcrop of the magnetic shale, whose dip is estimated from the shape of the magnetic profile at the surface. The location of the Main Reef under cover of 2000 feet was thus inferred and later confirmed by deep diamond drilling.

Modern aeromagnetic surveys, using a fluxgate or proton free-precession magnetometer carried by an aeroplane or helicopter, have had a great vogue since the Second World War for helping to locate iron, nickel and ilmenite ore bodies, and especially for outlining regional structures and delineating areas deserving closer inspection by other means. The magnetometer is commonly flown 500 feet above ground and provides automatically recorded continuous profiles of the magnetic intensity of the rocks along prescribed lines of flight, a feature which largely offsets the lower degree of resolution afforded by aeromagnetic as compared with ground magnetic surveys. Certainly these surveys provide a rapid and comparatively cheap method of depicting the grain of the country and of locating anomalies which may be interpreted by the geologist in terms of ore bodies, basic rocks, faults, fracture zones and variations in depth to the crystalline basement. The airborne technique is at a disadvantage, however, in the examination of small-scale, detailed structures. It is often preferable to carry out geophysical prospecting from the air before the commencement of systematic field work on the ground, so that the field geologist equipped with aeromagnetic and photo-geological maps can be constantly on the alert to explain the geophysical anomalies and if need be to challenge or elaborate upon the photo-interpretations.

Gravimetric methods of prospecting depend on the correlation between geological features and changes in the specific gravity of rocks. Sensitive instruments, such as the gravity meter capable of detecting variations in the force of gravity of one or two parts in one hundred million, may be used to measure these small changes, which can then be interpreted in terms of probable mass distribution below the surface, leading to tentative assessments of the local geological conditions. Incidentally, gravity measurements can now be made in an aeroplane or by lowering an instrument to the sea bed. Gravimetric methods have been extensively used in oil exploration, but their application to the search for ore has been much restricted by the high cost of field investigations and by the fact that abnormally large density-contrasts or unusually large ore bodies are required to produce significant gravitational response. Nevertheless, they have been successfully applied to the detection of chromite bodies in serpentine, massive sulphide deposits and big deposits of iron ore, and when used in conjunction with electromagnetic surveys they constitute a promising method of locating various kinds of sulphide bodies.

Gravimetric methods may be of indirect assistance in mineral exploration by providing information about regional structures associated with ore deposits. For example, in Cornwall negative gravity anomalies have been obtained over known granite masses which happen to be genetically related to tin-tungsten-copper lodes, and a similar anomaly in the North Pennine orefield, probably caused by a deeply buried intrusive granite, coincides approximately with the geographical limit of barytes veins in that area. Under favourable conditions, therefore, the gravimetric technique might be capable of locating concealed granite masses, which could be accompanied by ore deposits.

An outstanding success in selecting areas to be tested by drilling was achieved by carrying out a torsion balance survey during the search for gold in the Orange Free State (Frost and others, 1946). The problem involved finding the relatively light gold-bearing Witwatersrand quartzites and conglomerates at comparatively shallow depths. Previous boreholes had penetrated thousands of feet of heavy basic lavas (the Ventersdorp Series) beneath a still younger unconformable cover of Karroo sediments, without reaching the auriferous Witwatersrand Series. With the aid of gravity surveys, however, it was possible to indicate where the lavas are thin or absent, and subsequent drilling in these areas actually intersected the gold-bearing reefs in an uplifted horst block beneath a capping of about 1000 feet of Karroo beds. This achievement is all the more remarkable because the nearest outcrop of Witwatersrand rocks is seventy miles away. The recent spectacular development of the Orange Free State goldfield thus bears witness to a triumph of geophysical prospecting.

Electrical methods of exploration were first used by R. N. Fox, who in 1830 discovered that natural potential differences exist between different parts of an oxidising ore body; he thereby initiated the spontaneous polarisation technique of prospecting. This simple, rapid and cheap natural earth current method is unique among electrical methods because no currents are artificially introduced into the ground, the oxidising ore body itself acting as a battery which produces currents detectable at the surface. It is particularly useful for locating sulphide ore at shallow depth, but has the serious disadvantage of responding readily to fortuitous variations in surface conditions.

In most of the wide variety of surface electrical methods of prospecting, direct or alternating current is artificially introduced into the ground between a pair of earthed electrodes, and conducting bodies are located by means of current or potential-drop measurements. Two of the most useful techniques, the resistivity and electromagnetic, depend upon the contrast in resistivity between an ore body and its enclosing rock, or between any two rock formations. In the resistivity method direct current is passed into the ground between two outer electrodes and the voltage drop between a pair of inner electrodes is measured. Its chief role is in structural investigations, such as the tracing of faults or the contact between adjacent formations, and in determining variations of thickness of an overburden or the depth of gently dipping formations. Only rarely can the resistivity technique reveal the presence of a good conducting ore body.

Both for general reconnaissance and especially for the intensive study of areas suspected to contain ore bodies, various electromagnetic methods are widely favoured, for they yield much information concerning the shape and location of hidden ore bodies or other conducting zones. In some of these techniques alternating current is passed through a large horizontal loop of insulated cable suitably disposed on the ground so that electromagnetic waves spread out in all directions from the energising loop. These waves stimulate currents by induction in any conductive body, causing it to re-radiate a secondary induced field whose effects can be measured at the surface by portable search coils. Among the many advantages of this inductive method is its efficacy in mountainous regions, in deserts and snow-laden areas, over ice-covered lakes and in districts containing non-conducting surface rocks. Its application has resulted in the discovery of many massive and disseminated sulphide deposits.

Recently there has been a flurry of activity in airborne electromagnetic surveys, particularly in Canada, for the detection of massive sulphide bodies under shallow cover. In this technique a transmitting coil, mounted upon an aeroplane or helicopter, carries an alternating current whose magnetic field induces current in the conducting ground, and this in turn re-radiates an electromagnetic field to a second coil mounted in a 'bird' towed by the plane. Both high and low frequency currents are used simultaneously, the final geological interpretations being based on the form of the phase shift curves between the transmitted and resultant fields. The presence of a good conductor is disclosed by a sharp peak in the low frequency profile and a less pronounced one in the high frequency curve. Since the height of the electromagnetometer above the ground affects the form of the profiles obtained, it is advisable in rugged terrain to tow the instrument by means of a contour-flying helicopter. This speedy and economical form of large-scale exploration can yield valuable information about the disposition of major lithological formations and structural features such as faults, besides being applicable to the direct search for mineralised ground. As with all electrical methods of prospecting, however, it is only effective to comparatively shallow depths of about 300 feet.

A great variety of techniques are at the disposal of the prospector searching for radioactive ores, and the successful outcome of the intensive search for uranium during the past fifteen years bears eloquent testimony to their efficiency when used under geological control. Most of the discoveries have been made by using Geiger-Müller and scintillation counters in areas previously known to be hospitable to radioactive ores. These instruments measure gamma radiations from near-surface occurrences of uranium, thorium or potassium which produce secondary electrons that are amplified by gas multiplication in the Geiger-Müller tube, or produce flashes of light from a thallium-activated sodium iodide crystal which are amplified with the aid of a photo-multiplier tube in the scintillation counter. The instruments will not pick up radiations from radioactive minerals buried under a few feet of earth, while unwanted radioactivity effects such as those due to radon concentrations along water-logged fissures may give misleading results.

On a pedestrian search for radioactive minerals in virgin territory it is usually advisable to look for conspicuous signs of copper, cobalt, silver or other minerals that are commonly associated with uranium rather than to prospect solely for that element. In car-borne and airborne radiometric surveys, the latter generally flown at a height of 500 feet, it is customary to use high sensitivity scintillation counters. Bowie and his associates (1958), after completing an airborne radiometric survey of Cornwall, conclude that 'the use of sensitive scintillation counters in aircraft provides an effective and economical method of secondary prospecting in an area considered on geological and geochemical grounds to be hospitable to uranium or thorium mineralisation. For primary prospecting in areas where little is known of the geology it is unlikely to prove economical to search for radioactive minerals; but the simultaneous operation of radiometric, magnetic and electromagnetic equipment, if well planned, is much more likely to be remunerative. Airborne radiometric surveys, besides being useful in the discovery of radioactive mineralisation, would undoubtedly be of value in the broad regional mapping of relatively unknown territory.' The radiometric or gamma logging of various kinds of drill-holes is a routine operation in many fields, not only in searching for radioactive ores, including potassium salts, but also for detecting feebly radioactive marker horizons during oil, gas and mineral exploration.

Before closing these brief references to geophysical techniques mention should be made of the use of portable ultra-violet lamps when prospecting on the surface or underground for the tungsten mineral, scheelite, which responds to short-wave radiations by emitting a bright blue fluorescence. Within recent years many important scheelite deposits have been discovered by this simple means of detection, which can also be applied to the recognition of the zinc silicate, willemite, several uranium-bearing minerals and usually to fluorite.

Geophysical prospecting came to the forefront with startling rapidity in 1925 with its successful application to the discovery of salt domes in Texas and Louisiana. Since then it has played a major role in oil-field exploration, where the prizes of success are very much larger and more quickly realised than those in mining. Its career in the mining industry has hitherto been generally disappointing, not because of inherent defects in the methods but often owing to their unbridled use by charlatans and over-optimistic advocates lacking in geological acumen. Until quite recently the mining industry itself has been much to blame for its gullible approach to geophysical prospecting, without properly appreciating its limitations and the fact that its results are usually open to various alternative interpretations. Moreover, the industry has only latterly sponsored adequate research into the development of new techniques of prospecting for minerals, and has often failed to insist that all mineral exploration projects should be under strict geological control. With a more realistic understanding of the scope of different geophysical techniques, used separately or in close combination, with improved equipment and better trained personnel, it is certain that applied geophysics will play an increasingly vital part in future mineral exploration as an aid to geology in finding extensions of known ore bodies, in locating virgin buried deposits, in tracing formations and contacts, and in providing evidence of geological structures.

5. GEOCHEMICAL PROSPECTING

The latest outstanding contribution to the technique of mineral exploration is that of geochemical prospecting, first practised in the U.S.S.R. before the Second World War but only employed to any considerable extent elsewhere during the past decade. Geochemical methods of prospecting depend on the presence of significant traces of metals dispersed in the rocks and soils around an ore body, in the plants and trees growing on those soils, or in the waters and sediments of streams and lakes draining the mineralised areas. Thus, although there may be no visible manifestation of mineralisation, the occurrence of concealed mineral deposits may nevertheless be revealed by the detection of anomalous concentrations of metals in the rocks, soils, waters, sediments or vegetation in the vicinity of ore bodies. Since the concentrations involved are usually very minute, rapid trace analytical techniques, including colorimetric, chromatographic and spectrographic methods, have been specially devised to detect them. Although geochemical methods are still in their infancy they are now used extensively in regional mineral reconnaissance and in local exploration, often in close conjunction with geological mapping and geophysical measurements on the ground. Their application has already led to the discovery of a wide variety of ore bodies in latitudes ranging from arctic to tropical, and in future they must surely be regarded as an almost essential and integral part of any well-planned prospecting programme.

Geochemical techniques may be applied in various ways according to the primary or secondary nature of the metal dispersion patterns, and according to the media wherein the anomalies may be detected by systematic sampling and analysis. Primary dispersion aureoles containing diagnostic trace elements may be developed by hydrothermal solutions impregnating the wall-rocks around an ore body. Such aureoles may actually yield encouraging chemical indications at much greater distances from the ore body than any visible manifestation of mineralogical changes in the wall-rocks. Systematic geochemical analysis of the wall-rocks may thus increase the target of ore-search, or indicate the most promising areas to investigate where obvious wall-rock alteration is widespread. The analysis of rocks from dispersion aureoles is likely to be most useful in underground exploration, in places where it would be an advantage to know whether a cross-cut or drill-hole is close to ore. For example, Hawkes (1957) quotes how systematic rock analysis demonstrated that the lead and zinc content of a particular limestone rose towards the end of an abandoned cross-cut in the Tintic district, Utah; subsequent extension of this cross-cut broke into a new ore body within a distance of ten feet.

Primary 'leakage' dispersions related to blind deposits are produced by residual solutions passing upwards along outlet channels away from the main sites of ore deposition. Their detection at the surface may portend the presence of valuable ore at depth. The best recorded example of such a leakage halo over blind ore is at Tintic, Utah, where positive anomalies were disclosed by the analysis of surface rocks and soils up to 1000 feet vertically above deeply buried lead-zinc deposits. A similar leakage halo occurs in the Ashover district in Derbyshire (Webb, 1958), where the analysis of residual soil revealed abnormal concentrations of lead and zinc which are probably related to productive veins in limestone at a depth of 700 feet below ground. The detection of leakage anomalies is certainly no guarantee that ore exists in depth, but when interpreted in the light of local geology and geophysical evidence they may provide an added incentive for sub-surface exploration.

Secondary dispersion patterns develop during weathering and erosion, and may be detected in residual and transported soils, in plants and trees, and in stream waters and sediments. Providing the overburden is residual in origin, abnormal concentrations of trace elements are almost invariably developed in the soil overlying a sub-outcropping ore body. Many factors, including topography, soil type, pH and the nature of the bedrock, affect the size and form of the anomalies. As a rule, however, the application of geochemical soil surveys in areas of residual soil has proved to be so simple and effective that they are now accepted as a part of conventional exploration practice. Good results are usually obtained by sampling the soils at twelve to eighteen inches below ground. Above narrow steeply dipping ore bodies typical anomalies, where the metal concentrations are several times greater than the background values, range up to several hundreds of feet in width for soluble metals such as copper and zinc, but perhaps no more than thirty feet or so for chemically inert metals like lead and tin. In some cases the dispersion of the valuable ore metal may be so restricted that it is better to investigate the distribution of associated 'pathfinder' elements. Thus in Southern Rhodesia and Sierra Leone, arsenic and antimony in soils have been used as indirect pathfinder elements in the search for arsenical and antimonial gold deposits. In parts of Idaho prospecting for arsenical cobalt ores is narrowed down by testing the residual soils for arsenic, since that element is much less mobile than the more widely dispersed cobalt. On the other hand, where molybdenum is associated with copper ores the latter may best be discovered by sampling the soils for molybdenum since it is more mobile than copper and consequently sets up a wider geochemical halo.

Even where the ore bodies are covered by transported overburden, such as glacial till, it may be possible to find anomalous concentrations of metals by taking deep samples with long augers. The metals may become embodied in the overburden by mechanical incorporation during glaciation, by the leaching of soluble metals from an underlying ore body by groundwater, or by the extraction of metals by tree-roots followed by their return to the surface soil through decay of the flora. Positive anomalies have been detected where copper, lead, zinc and nickel deposits are concealed by transported glacial material up to tens of feet in thickness.

Biogeochemical techniques try to locate mineral deposits by the chemical analysis of vegetation. Plants and trees absorb metals from the soil through their roots and concentrate them in leaves, twigs and other organs, so that the systematic sampling and analysis of vegetation may reveal the presence of geochemical anomalies related to buried ore. One advantage of this method of exploration is that in areas of deep transported overburden, such as glacial drift, samples collected by trees through their extensive and deeply penetrating root systems may sometimes be more significant than near-surface soil samples. In the vast majority of cases, however, anomalies disclosed by the analysis of vegetation are not so well defined as those detected by the analysis of soils; which themselves normally contain metals liberated during the decay of organic debris.

Geobotanical methods of prospecting were foreshadowed 400 years ago by Agricola in *De Re Metallica*, where he recorded the effect of hidden metal veins on nearby vegetation, observing that 'where a vein extends, there grows a certain herb or fungus which is absent from the adjacent space'. These techniques are based on the distribution of characteristic plant species or variations in the plant ecology related to abnormal metal concentrations in the soil. High concentrations may modify the colour or morphology of the flora, or determine whether a particular species of plant will thrive or be poisoned. In some cases 'indicator' plants grow exclusively on soil containing an excessive amount of a certain element. For example, on the Colorado plateau, *Astragalus pattersonii* (locoweed), which is highly toxic to cattle and sheep, grows only on soils rich in selenium, and since selenium is there a pathfinder element associated with uranium ores the distribution of the locoweed virtually indicates the presence of radioactive deposits. The zinc violet, *Viola calaminaria*, thrives on soils overlying zinc deposits in Central Europe and elsewhere, and over certain copper deposits in Arizona the bright orange blossoms of the California poppy depict the extent of oxidised ore, while in the Congo–Rhodesian copperbelt a small blue flower, *Acrocephalus beertii*, has long attracted prospectors to copper-cobalt showings. It must be emphasised, however, that indicator plants are merely encouraging signs and not infallible guides to ore.

Whereas geochemical soil, rock or vegetation anomalies are usually confined to the immediate vicinity of the parent ore bodies, abnormal concentrations of metals may sometimes be detected in the surface drainage system up to several miles downstream from the centre of mineralisation. The chemical sampling of groundwaters, streams or alluvium is analogous to the panning technique used in alluvial prospecting, for in both cases the trail of increasing concentration of the wanted material is followed upstream to its source in the 'mother lode' or target area. During the past decade most of the earlier studies of metal dispersion in the drainage system were solely concerned with the amount of heavy metals (Cu, Pb and Zn) in stream waters, but although a number of successes have been achieved by this method of prospecting it suffers from several disadvantages. 'These arise chiefly from the extreme analytical sensitivity required and the marked susceptibility of the metal content to vary, seasonally and diurnally, according to the incidence of rainfall and changes in the pH, organic content, micro-organisms and other factors' (Webb, 1958).

Latterly, more attention has been focused on the analysis of stream, swamp and lake sediments, since their metal content is less affected by these drawbacks. Moreover, dry stream channels may be investigated, rapid partial extraction chemical techniques can be applied in the field, large-scale reconnaissance operations can be carried out more efficiently, and the samples may be examined spectrographically for a wide range of elements and also stored for future reference. By the analysis of stream sediments anomalies have been detected for distances exceeding two miles downstream from an ore body. There is now no doubt that, despite some of its limitations, this type of geochemical reconnaissance shows great promise as a preliminary means of assessing the mineral potentialities of large areas with a view to delimiting focal points for subsequent detailed geochemical and geophysical investigations. It should be added that both in Russia and in North America exploration parties sometimes carry mobile spectrographs, worked off portable generators, in order to make comprehensive analyses in the field.

It is reported that the use of geochemical prospecting techniques is now mandatory for the 6000 or so exploration parties sent out annually by the government of the U.S.S.R., and that the Russians have been analysing about six million samples each year, equivalent to three times the rate of the rest of the world. Geochemical survey maps, indicating localities of various metal concentrations determined by water, soil and sediment analyses, have already been published for enormous areas in Kazakhstan and elsewhere, and it is claimed that many recent discoveries are rich in base metals, antimony, beryllium, mercury, nickel, tin, tungsten or vanadium. It is not too much to hope that in the near future similar geochemical surveys will be carried out in other parts of the world, and that maps will be issued illustrating the distribution and concentration of various elements within different regions. Such maps would be a boon to prospectors.

6. DRILLING

The presence of concealed mineral deposits, whether inferred from geological, geochemical or geophysical observations, can often be established only by drilling. Exploratory drilling may be undertaken solely to gain such geological information as the stratigraphical sequence, the position of a contact or structural detail, but on the other hand it may be planned specifically to locate an ore body, to determine the nature and extent of an alteration halo, or to provide the means for carrying out electric and radioactive logs.

Various types of drill are in use, ranging from hand augers for testing unconsolidated near-surface material, to diamond drills capable of yielding cores from depths of many thousands of feet. Percussion or churn drills, which bore vertical holes to depths of up to 2000 feet by means of a bit suspended from cables or rods, may be employed for proving alluvial deposits, for penetrating heterogeneous glacial drift, or for drilling through rocks which shatter well under impact, in order to identify structures or explore for mineral deposits. Rotary drills include those which use drag- or roller-bits, usually non-coring, and those with diamond, tungsten carbide or other abrasive bits which provide cylindrical rock cores. The choice of a drilling method depends on a wide variety of factors (McKinstry, 1948; Weiss & Eastwood, 1954), but under conditions where reasonably good core recovery can be anticipated, the favourite machine is the diamond drill, which not only bores horizontally, upwards or downwards but also yields cores capable of providing a wealth of geological and geochemical information. These drills range in size from small rigs portable by one man and capable of boring to nearly 200 feet in good ground, to huge machines that can explore to depths of more than four miles. Different kinds of survey instruments may be lowered down the holes to determine their inclination and azimuth, and if necessary the borings can be deflected in one or more directions by the insertion of wedges at appropriate depths. Rightly used the diamond drill is one of the most useful tools at the prospector's disposal.

7. FUTURE OUTLOOK

The spectacular success of mineral exploration in the U.S.S.R. and of the intensive search for uranium during the past decade indicate what may be achieved when there are strong incentives to discover urgently needed minerals. Known reserves of bauxite, chromite, copper, iron, manganese, phosphates, potash, sulphur and titanium are adequate to meet all likely requirements for at least the next fifty years. Moreover, even though the proved reserves of most other mineral raw materials are much less comforting, I am confident that the application of improved methods of prospecting, mining, mineral beneficiation and the treatment of low-grade ores will banish the bogy of mineral shortage. It is certain that innumerable ore bodies still await discovery beneath a concealing blanket of soil, swamp, forest or barren rock, and that if it were possible to peer through this cover a multitude of unsuspected mineral deposits would be revealed.

The use of aircraft has revolutionised and speeded up mineral exploration by providing the means to produce aerial photographs, to carry out geological reconnaissance with the help of helicopters, to undertake geophysical surveys and to transport men, supplies and equipment to remote or otherwise inaccessible areas. Both quantitatively and technologically prospecting has made rapid strides within the past decade and it will continue to do so if the demand for minerals persists. Nevertheless, in most countries outside the U.S.S.R. the effort expended on mineral exploration is much too small. There are not nearly enough geologists, geophysicists or geochemists actively engaged in the search for minerals, and there is certainly a dearth of geologists adequately trained in the techniques of mineral exploration. A basic training in geology, including photo-interpretation, supplemented by postgraduate instruction in mining geology and methods of prospecting affords an excellent basis for the kind of recruits needed for mineral exploration, provided they are imbued with the spirit of adventure and enquiry and have the perseverance to overcome adversities.

There is still scope for the independent geologist and lone prospector, as recently testified by their many discoveries of uranium ore, but the high cost of the changed approach to prospecting, whereby many thousands of square miles of territory are intensively explored by geological, photogeological, geophysical and geochemical methods, means that the future search for minerals will be predominantly in the hands of large organisations. Integrated programmes of exploration using various techniques in unison or in sequence under strict geological control is likely to be the most fruitful pattern of the future. In parentheses, the potentialities of the ocean floor must certainly not be ignored, for recent research has demonstrated that millions of square miles of the ocean bottom in the south-east Pacific are covered by a sludge containing abnormal concentrations of manganese, iron, cobalt and copper. Indeed, the day may not be far distant when these and other metals will be raised from Davy Jones's locker!

The search for epigenetic mineral deposits during the past generation has been largely empirical and dominated by the notion that they were mainly deposited from hydrothermal solutions of igneous affiliation, the ores being emplaced in fractures or by replacing favourable host rocks under the guiding influence of structural features. Latterly, however, the role of hydrothermal solutions has been denigrated in certain quarters in favour of a resuscitated and modernised idea that in many cases the metals were originally deposited syngenetically within sediments, tuffs, basic lavas and intrusives, to be subsequently concentrated in fractures, pore spaces or replacement deposits by processes of metamorphic activation, lateral secretion, diffusion or granitisation. To an assessment of these divergent views I hope to return on some future occasion, for their resolution must profoundly affect on the philosophy of future mineral exploration.

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The Rhaetic of the Bridgend District, Glamorganshire

by E. H. FRANCIS

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ABSTRACT: The full Rhaetic succession in the Bridgend district is established. The dominantly sandy Lower Rhaetic is subdivided into three parts, here named Lower Sandstone, Black Shales and Upper Sandstone. The Lower Sandstone rests unconformably on the Keuper and is itself overlapped by the Black Shales and Upper Sandstone. In the Upper Rhaetic the Cotham Beds consist mainly of red and green marls with sandy pockets and with impersistent beds of detrital limestone like Sutton Stone. A similar rock forms the base of the Lower Lias (*Ostrea*-beds) resting unconformably on older strata.

Notes are included on the petrography of the sandstones and on the morphology of fossil phosphate occurring in them. The heavy minerals and the phosphate together serve to distinguish the Lower Sandstone from the Upper.

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1. INTRODUCTION

THE DISTRICT described falls almost entirely within the Bridgend Sheet (261,262) of the New Series One-inch Geological Map of England and Wales; it extends in a narrow tract, some nine miles long, from Pyle in the west to St. Mary Hill in the east (Fig. 1). Between Pyle and Bridgend the Rhaetic and other Mesozoic rocks, folded into a shallow syncline, are faulted against Upper Carboniferous rocks in the north and are partly faulted against, and partly overstep, Carboniferous Limestone in the south. East of Bridgend the Rhaetic forms a narrow outcrop repeated, in places, by faulting.

Throughout the district the Rhaetic includes unusually thick sandstones. These were first noticed by De la Beche (1846, 252) and later by Tawney (1866), who correctly correlated those at Pyle, but wrongly referred those at Bridgend to the Keuper. The error was pointed out shortly afterwards by Bristow (1867, 205). In the more detailed account (Strahan & Cantrill,

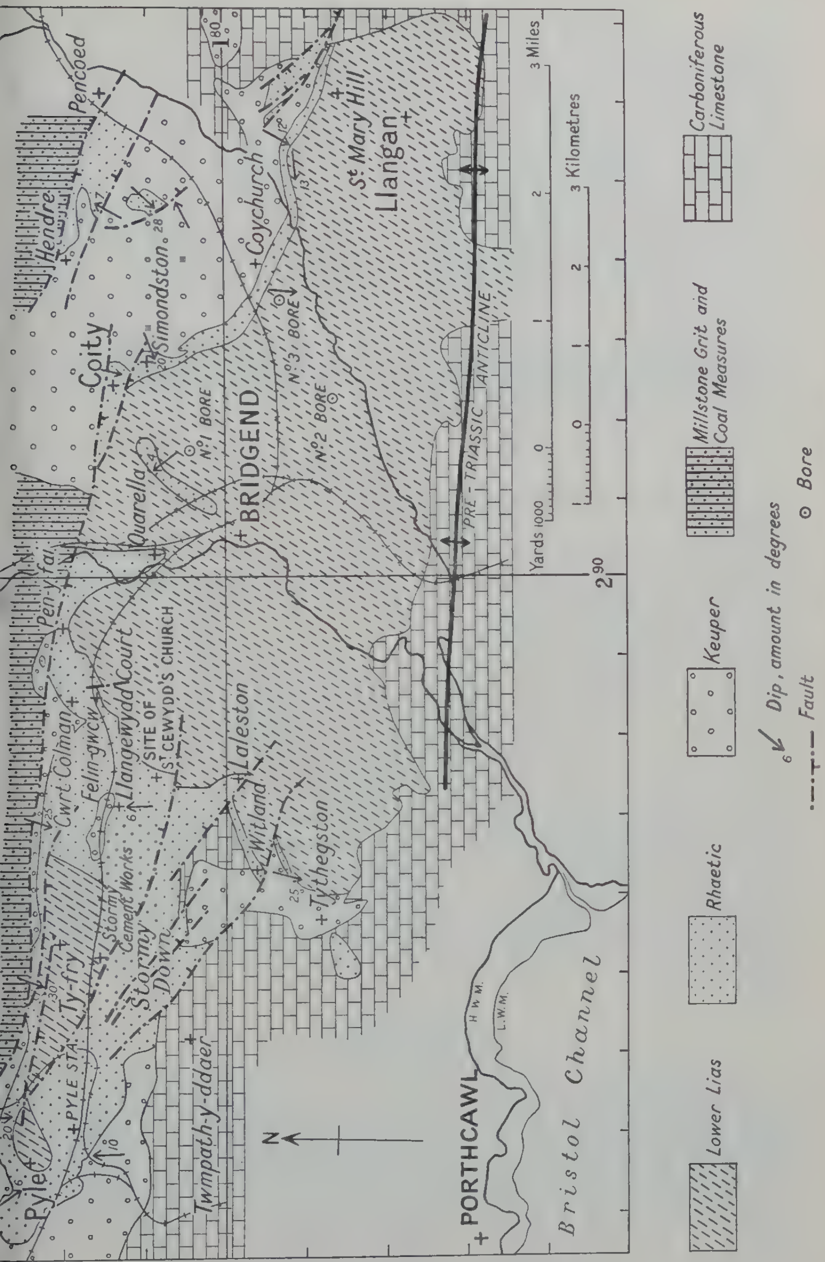


Fig. 1. Geological Map of the Bridgend District, Glamorganshire

1904) which followed the six-inch mapping by the Geological Survey, the sandstones were assigned, more precisely, to the Lower Rhaetic. This Survey memoir, like some earlier accounts, also describes green and red marls and rocks resembling Cotham Stone and Sutton Stone, at higher horizons than the sandstones. The green and red marls, thought by Strahan to represent a return to Keuper conditions of deposition, were assigned by him to the zone of *Pteria* (*Avicula*) *contorta*; the Sutton Stone was recognised as Upper Rhaetic. Richardson (1905, 410), whose investigations are the most recent, described the green and red marls as Upper Rhaetic, but concluded that several outstanding problems of correlation remained to be solved.

New exposures encountered in the course of mapping, together with records of three borings, have helped to determine, for the first time, the full succession in the district.

2. SUCCESSION

The following succession, showing maximum thicknesses, has now been established:

		ft.	in.
LOWER LIAS	*Ostrea*-beds		
UPPER RHAETIC	Cotham Beds	20	0
LOWER RHAETIC	Upper Sandstone	35	0
	Black Shales	6	7
	Lower Sandstone	20	0
KEUPER	Grey Marls, Tea Green Marls or limestone conglomerate ('Dolomitic Conglomerate')		

(a) Lower Sandstone

The Lower Sandstone is a white or yellow, medium-grained rock weathering grey; it is friable at the base but hard at the top. Traces of galena occur on the joint- and bedding-planes and lamellibranchs have been recorded at one locality (p. 167). The sandstone rests unconformably on Keuper. It ranges in thickness from twelve to twenty feet to the west of Bridgend, but east of the town it is thinner and is overlapped by younger strata.

(b) Black Shales

The base of the Black Shales is formed by a thin pebble-bed which rests on the uneven top of the Lower Sandstone. The pebble-bed contains poorly preserved fish and saurian remains. It is succeeded by black and dark green shales with nodular limestones. Lamellibranchs are common in the lower part of the shales and fish-remains occur at several horizons, the most notable being a nodular, pebbly limestone about midway in the shales.

(c) Upper Sandstone

The basal layers of the Upper Sandstone are fine-grained, thin-bedded, soft and drab brown, and are intercalated with brown, blue and green shales and clays. In one locality (p. 164) these argillaceous beds are predominant. The middle and thickest part of the Upper Sandstone is medium-grained, massive, and white, yellow or pale green; in a few places it is calcareous. The topmost few feet are hard, brown-mottled and have a calcareous cement. Lamellibranchs and gastropods, which occur commonly at several horizons throughout the Upper Sandstone, are poorly preserved except in the fine, flaggy beds at the base.

'Quarella Stone' is sometimes used as a general term for Rhaetic sandstone (e.g. Pringle & George, 1948, 85) although the Lower Sandstone is unknown at the quarry which gives the stone its name. For this reason, and also because it may imply certain commercial properties peculiar to the Upper Sandstone, the term is here restricted to the latter.

(d) Cotham Beds

The beds overlying the sandstones are here, for the first time, specifically assigned to Cotham Beds partly on lithological grounds and partly on the occurrence of *Chlamys valoniensis* at the top. They consist of marls, soft marly and harder concretionary limestones (some pseudo-brecciated) and pockets of red and green sandstone. These pockets resemble structures in the Upper Rhaetic of North Yorkshire (Raymond, 1955, 11) where they are ascribed to contemporaneous slumping. There are also thin, impersistent beds of detrital limestone which resemble Sutton Stone.

The lowest few feet of the marls and limestones are mainly cream-coloured, with a dendritic carbonate veining which continues down into the underlying sandstone. The upper, thicker portion of the marls is dominantly green though red patches also occur. A fine-grained argillaceous limestone found at or near the top of these marls is taken here, as by Strahan (1904, 51), to represent the Cotham Stone.

3. EXPOSURES

(a) Pyle

The Pyle Inn Quarry (828828)[1] described by Strahan (1904, 55) lies 400 yards north of the cross-roads at Pyle and is being obscured by building at the time of writing. The succession there may be summarised as follows:

---

[1] Grid references lie within the 100 km. squares 21 (SS) and 31 (ST).

		ft.	in.
UPPER SANDSTONE	Sandstone, soft, thin-bedded, ripple-marked and argillaceous with intercalated shales and clays at the base; massive, with bright green shale partings above	13	7
BLACK SHALES	Shales, black and green, with nodular limestones containing fish-remains	6	4
	Grit, in pockets, with rounded pebbles and indeterminate fish-remains		3
LOWER SANDSTONE	Sandstone, white, gritty at the top, soft and yellow below; massive	12	0

When recently examined the base of the section was overgrown, but Strahan saw green Keuper marls beneath the Lower Sandstone. In addition to fossils previously listed, *Chlamys valoniensis* (Defrance), *Protocardia rhaetica* (Merian), and *Pteria contorta* (Portlock) have been found in the lower part of the shales; the upper part is unfossiliferous. The Upper Sandstone contains *Cercomya praecursor* (Quenstedt) and *P. contorta* in addition to those forms recorded by Strahan.

Across the road from Pyle Inn higher beds were once quarried behind St. James's Church (824826). They have now become obscured by refuse from a nearby building site, but in 1948 the following partly overgrown section was visible:

		ft.	in.
COTHAM BEDS	Marls, green and red		
	Limestone, poorly bedded, cream-coloured, amorphous with calcite veining and bands of green and red marls; lenses of bright green sandstone at the base ... ... more than	6	0
UPPER SANDSTONE	Sandstone, finely mottled, brown, calcareous ...	5	0
	Sandstone, massive, medium-grained, white or pale green at top; finer-grained with green micaceous partings below	16	0

The lowest of these beds resemble those at the top of the Pyle Inn Quarry. The Upper Sandstone is therefore estimated to be about thirty feet thick at Pyle.

A short distance to the west of Pyle Railway Station and about half a mile south of the church the base of the Lower Sandstone is exposed in a road-cutting (827818). About twenty-four feet of black and grey shales with nodular argillaceous limestones are visible beneath the sandstone. These shales and limestones, representing the Grey Marls, are seen to be underlain by green, red and yellow marls (Tea Green Marls) in exposures 500 yards to the west.

By contrast, the base of the Lower Sandstone rests directly on Tea Green Marls in the bank of a stream one and a half mile east of Pyle

(848824). Several faults cross the stream south of this exposure. At one of these faults, 250 yards west of Ty-fry, the Upper Sandstone forms a waterfall (848823) and the following strata are exposed:

		ft.	in.
COTHAM BEDS	Marls, green and yellow	4	5
	Limestone, soft, cream-coloured, with carbonate veining	6	9
UPPER SANDSTONE	Sandstone, brown, mottled, hard, calcareous, with carbonate veining	8	6
	Sandstone, medium-grained, yellow and pale green	6	0

The faulting has caused the Cotham Beds to be repeated. Below the waterfall they contain an impersistent bed, up to twelve inches thick, of tough, blue-grey detrital limestone possibly like that seen by Woodward (1893, 114) close above the base of the Lias in the Stormy Cement Works Quarry, half a mile to the south-west. Above the waterfall the Rhaetic–Lias junction is obscured, but near its estimated position at the top of the marls there are large blocks of fine-grained, white-weathering argillaceous limestone very like the rock at Melin Cwcw taken by Strahan (1904, 53) to represent the Cotham Stone.

(b) Stormy Down

The lowest Rhaetic strata exposed at Stormy Down are seen in two contiguous disused quarries at the foot of the Down, 400 yards south of the old lime works. The following section was measured in the eastern quarry (851813):

		ft.	in.
UPPER SANDSTONE	Sandstone, brown, fine-grained, flaggy, with thin partings of brown, green and blue clay and dark, dendritic markings. *P. contorta*	7	10
BLACK SHALES	Shales, dark green, rubbly, with carbonised wood fragments and dendritic markings	3	0
	Shales, brown, with a nodular limestone, up to 6 inches thick, containing fish-remains		10
	Shales, dark green, with thin nodular limestones. Poorly preserved lamellibranchs and fish-remains	1	0
	Pebble-bed, with abundant, but poorly preserved, fish-remains		2–7
LOWER SANDSTONE	Sandstone, hard, massive, white and yellow, with traces of galena on the joints	18	0

The quarry floor is flooded, but from local information it appears that the Lower Sandstone is here altogether twenty feet thick and is underlain by Grey Marls like those in the road-cutting near Pyle Station.

Some 150 yards farther south, the most recently worked quarry faces are crossed by an east-south-east disturbance which is now better exposed than formerly (Strahan, 1904, 56). It appears to have little vertical displacement, but some horizontal movement is suggested by minor folding along axes at right angles to the line of disturbance. Small-scale thrusting is also visible. The succession is as follows:

		ft.	in.
UPPER SANDSTONE	Sandstone, medium-grained massive, white, yellow or pale green	12	0
	Grit, coarse, pebbly	6–12	0
	Clays, brown, ochreous, blue and green, with carbonised wood	15	0

The lowest ten feet of this section was measured in a temporary pit-like exposure which had been formed overnight, perhaps as a result of caving in the Carboniferous Limestone below. The clays are considerably thicker than those intercalated near the base of the Upper Sandstone elsewhere. A ditch opened between Pyle and Bridgend in 1948 showed the clays to continue, still thick, as far east as the site of St. Cewydd's Church (875809), but farther east this part of the succession is dominantly sandy as at Pyle. The coarse grit is also very localised. It is soft and friable and contains large, rounded pebbles of quartz and flakes, up to six inches long, of green and yellow Keuper marls. In places the high content of carbonised wood gives the bed a dark grey colour.

These are the youngest of the Rhaetic beds now exposed at Stormy Down. In former times, however, Upper Rhaetic and Lias strata were seen at the foot of the Down in a quarry at Stormy Cement Works (852816). The Upper Rhaetic there consists of at least nine feet of grey and green marls overlain by nine or twelve inches of black shales containing *Chlamys* [*Pecten*] *valoniensis* (Tawney, 1866, 77; Woodward, 1893, 114). The shales were succeeded, in turn, by two feet two inches of limestones with shale partings which, though previously classed as Rhaetic, are now included in the Lias on the basis of the pre-*planorbis* Beds fauna obtained from them by Tawney.

At the top of Stormy Down, south of the sandstone quarries, the Mesozoic rocks are faulted against Carboniferous Limestone, which outcrops on both sides of the main road. In a disused quarry (844805) on the south side of the road, near Twmpath-y-ddaer, a mass of Rhaetic sediments has been preserved in a fissure now revealed by the quarrying of the enclosing limestone. The mass consists of blocks of Carboniferous Limestone set in a matrix of soft yellow limestone which has a dendritic calcite veining similar to that found in the Cotham Beds. There are, in addition, layers of pale, compact, argillaceous limestone similar to the rock locally taken to represent the Cotham Stone. At the base of the mass there is a thin, impersistent layer of yellow sandstone.

(c) Laleston and Tythegston

Rocks referable to the Rhaetic are exposed intermittently at the sides of the road to Porthcawl which branches off from the Pyle–Bridgend road near Witland (863797), 2300 yards east-south-east of the last locality and 1400 yards west of Laleston. South from the road junction red Keuper Dolomitic Conglomerate is succeeded by a yellow limestone conglomerate which has a sandy matrix and which is doubtfully referred to the Rhaetic. It is overlain, in turn, by green and red marls with nodular limestones, exposed a few yards south of Witland. In a field to the east the marls are succeeded, first by four feet of detrital limestones, then by *Ostrea*-beds. Some 400 yards to the south the limestones appear again, in an old quarry (862793), where they rest directly on Keuper as follows:

		ft.	in.
LIAS	Limestone, bedded, with *Ostrea* spp.	11	0
	Limestone, detrital, shelly	4	6
KEUPER	Limestone conglomerate, red	2	0

The green marls, presumably Cotham Beds, thus appear to be overlapped southwards by the detrital limestone which is itself overlapped farther to the south (Strahan, 1904, 54). The detrital limestone has a fauna which includes *Dimyopsis intusstriata* (Emmrich), *Liostrea hisingeri* (Nilsson) and echinoid (?Cidaroid) radioles; it is therefore referred to Lias rather than Rhaetic as thought by Strahan (1904, 54).

South-westward, just beyond Tythegston, where the Carboniferous Limestone crops out, Rhaetic rocks reappear in an ill-defined area strewn with boulders. In the overburden of the present limestone quarry on the north side of the Tythegston–Porthcawl road these boulders are mainly small and consist of fine-grained yellow sandstone. Traces of green, ochreous and red marls occur also, but their relationship to the sandstone is not determinable. At the side of the road and south of it are large boulders, some up to five feet across, of a conglomerate containing boulders and pebbles of pale, hard, sometimes calcareous sandstone, with less common blocks of Carboniferous Limestone.

(d) Llangewydd

North of Laleston, where the Rhaetic outcrop broadens, there are several small exposures of sandstone. One of these, at the roadside (873813) 150 yards east of Llangewydd Court, includes parts of both Upper and Lower Sandstone, with Black Shales between. At an old quarry (872808) 550 yards south of the last locality and 350 yards west-south-west of the site of St. Cewydd's Church there is twelve feet of the Upper Sandstone capped by green marls. The sandstone is calcareous, particularly adjacent to the joint planes.

(e) Cwrt Colman

The softer beds that crop out in the railway-cutting at Cwrt Colman (883815) are now largely overgrown. The succession, which was recorded in detail by Tawney (1866, 70), much resembles those at Pyle and Stormy Down as may be seen from the following summary:

		ft.	in.
UPPER SANDSTONE	Sandstone, white, yellow and pale green, becoming fine-grained with intercalated shales and marls towards the base	17	0
BLACK SHALES	Shales, black and green, with nodular limestones, one being a siliceous, micaceous bone-bed	6	7
LOWER SANDSTONE	Sandstone, white and yellow, massive, with coprolites at the top	8–10	0

The top of the Lower Sandstone is still visible. It is a pebbly bone-bed as at Pyle and Stormy Down. Some 300 yards to east-north-east, on the south side of the railway, is Felin-gwcw (Melin Cwcw) (885816), south of which Strahan (1904, 53) saw buff marlstone like Cotham Stone, green and red marls and rocks like Sutton Stone in that descending order. These are no longer visible, but beds nearly corresponding in horizon crop out intermittently farther to the west. In one old quarry, half a mile south-west of Cwrt Colman (878813), white marls with soft limestones are succeeded by green marls.

(f) Bridgend

Sandstones, about twenty-eight feet thick, are exposed rather more than half a mile east of Cwrt Colman in an old quarry (895820) at Pen-y-fai. The lower beds contain green shale partings and are of finer grain than the upper. All are referred to the Upper Sandstone.

Still farther to the east, sandstones next appear on the north side of Bridgend at Quarella Quarry (903807). The most complete section is now found on the north side of the railway near the place where it crosses the road to Coity:

		ft.	in.
COTHAM BEDS	Limestone, hard, fine, argillaceous, with conchoidal fracture (Cotham Stone)		3
	Marls, green and yellow, with nodular limestones	2	0
	Limestone, soft, cream-coloured, with green sandy layers	6	6
UPPER SANDSTONE	Sandstone, brown, mottled and calcareous at the top; massive, green and white at the centre; pale, argillaceous, with green shale partings at the base	25	0

This thickness of Cotham Beds conforms better with Richardson's record (1905, 407) than with Strahan's (1904, 51). Both earlier writers saw higher strata which they took to be *Ostrea*-beds, but these are now overgrown.

(g) Coity and Coychurch

The road between Coity and Coychurch runs in a south-south-east direction along the Rhaetic outcrop and almost parallel to the strike. The present road branches off from the old road at a point half a mile from Coity and in a cutting there (929806) the following rocks are exposed:

		ft.	in.
UPPER SANDSTONE	Sandstone, fine-grained, brown, flaggy, with intercalated green shales and clays	3	0
BLACK SHALES	Shales and clays, green and black	3	0
	Pebble-bed with teeth of *Sargodon tomicus* Plieninger and other bone and spiny remains		3
LOWER SANDSTONE	Sandstone, hard, white, medium-grained, becoming softer and yellow below, with '*Schizodus*' sp., '*S*' *elongatus* (Moore), *Myophoria postera* Quenstedt, *Gervillella praecursor* (Quenstedt)	3	4
GREY MARLS OF KEUPER	Shales, black, with a band of hard, argillaceous limestone near the top and a band of limestone conglomerate below	3	0

Nearer Coity, at Simondston (927809), flaggy beds with blue clay partings, all lower members of the Upper Sandstone, are again seen; they contain *Lima* (*Plagiostoma*) *praecursor* (Quenstedt), *Myophoria postera* and *Gervillella praecursor*. Keuper conglomeratic limestones crop out in the lane just behind Simondston, close to the estimated base of the Rhaetic.

Coarser beds of sandstone are exposed around the castle at Coity and along the road from there westward to Bridgend. They give way to hard mottled sandstones and green marls at the western outskirts of Coity. South of Coity the Lias is oolitic and its lower bands contain chert (Strahan, 1904, 71).

(h) Pencoed and St. Mary Hill

The faulted outcrops of Rhaetic rocks at Pencoed and St. Mary Hill are less well-exposed than formerly. At Hendre Quarry (947817), near Pencoed, the thirty-feet face of sandstone is still to be seen, but its junction with underlying Keuper Marls (Strahan, 1904, 33) is not. Similarly at St. Mary Hill it is necessary to refer to Strahan (1904, 50–1) to establish the downward succession of *Ostrea*-beds, 'White Lias', green and red marls, sandstone, green Keuper marls and Keuper conglomerate. The 'White Lias' is not described in detail; possibly it is the rock described by Bristow (1867, 204) as the Sutton Stone which he saw overlying the shales at Llangan and at St. Mary Hill Common.

(i) Cowbridge

Although some of the exposures near Cowbridge are south of the contemporary island and some distance beyond the margins of the Bridgend district, they are of interest in so far as they show a stage in the transition from sandstone to black shale (p. 177). A sandstone which crops out between How Mill and The Herberts (003723) rests on Keuper Marls and is succeeded by black shales (Richardson, 1905, 404); its stratigraphical position and its heavy mineral content both suggest correlation with the Lower Sandstone of the Bridgend district. The sandstone of Tre-gôf (Tre-gyff) (032712) rests on more than twelve feet of black shales described in detail by Richardson (1905, 400–1); it is therefore referred to the Upper Sandstone of the Bridgend district. Sandstones also presumed to be of this age crop out, five feet thick, at The Cross, St. Hilary (019728), where they contain partings of black shale. They are finer-grained than the Upper Sandstone of Bridgend, but are similar in content of both heavy minerals and fossil phosphate (pp. 171–75). From these exposures it would seem that the twofold subdivision of the sandstones persists beyond the island and beyond the sandy oolites representing almost the whole of the Rhaetic in the railway-cuttings at Cowbridge and St. Mary Church Road Station (Cantrill, 1904, 41–9).

4. BORINGS

Complete sections through the Rhaetic were obtained in three borings sunk in the area between Bridgend, Coity and Coychurch. For the purpose of this account they are numbered 1 to 3; their sites are shown on Fig. 1. Fossils obtained from Nos. 1 and 2 bores have been identified by Mr. R. V. Melville and are listed in the logs below.

(a) No. 1 Bore

The nearest bore to the Quarella Quarry is No. 1, sunk on Brackla Hill (916805) in 1937. Although the core was not examined by a geologist at the time, the borer's log, together with several specimens, is now lodged with Geological Survey records. The specimens pertaining to the Rhaetic (Bg 1967–2021) are numbered in groups of two to seven, each group representing a thickness of strata ranging from one to ten feet. This leaves room for a small margin of error in assessing the positions of each specimen within any one group. The following succession is based on the borer's journal and examination of the specimens:

		Thickness		Depth	
		ft.	in.	ft.	in.
LIAS	Limestones and shales	135	0	135	0
COTHAM BEDS	Marls, cream-coloured and pale green in patches, with sandstone pockets and calcareous veining	16	0	151	0
UPPER SANDSTONE	Sandstone, medium-grained, grey, purple and marly at the top, yellow or pale green with patchy calcareous cement below; ?*Modiolus* sp. indet. cf. *langportensis* Richardson & Tutcher	22	0	173	0
	Sandstone, flaggy, fine-grained, with thin partings of green shale	9	0	182	0
BLACK SHALES	Shales, black, with thin limestones and ?*M.* sp. indet. cf. *langportensis*	2	0	184	0
	Shales, black, with thin limestones and *Acteonina* (*Ovactaeonina*) sp. (The specimen is flattened, but it does not seem to agree with any of the four species figured by Moore (1861, pl. xvi, figs. 18–21) as '*Cylindrites*'.) *Myophoria inflata* Emmrich, '*Schizodus*' sp. juv., ? lamellibranch indet.; gastropod indet.; *Gyrolepis alberti* L. Agassiz, scale, *Saurichthys acuminatus* L. Agassiz, tooth; plant fragment indet.	2	0	186	0
LOWER SANDSTONE	Sandstone, yellow and pale grey, medium-grained with lamellibranch indet. and fish-fragments indet.	10	0	196	0
KEUPER	Marlstones, pale grey, with black shales	6	0	202	0
	Limestone conglomerate				

Mr. Melville states that the fossils between 184 and 186 feet are certainly Lower Rhaetic in age. He is doubtful, however, about the naming of the more indeterminate material above 184 feet particularly since it implies that the upper part of the Black Shales and the whole of the Upper Sandstone and overlying green marls should be correlated with pre-*planorbis* Beds.

(b) No. 2 Bore

No. 2 Bore (922787), sunk in 1942, was examined to a depth of 520 feet by Messrs. R. V. Melville & F. G. Dimes. In the following sequence items below 520 feet are based mainly on the borer's log:

		Thickness		Depth	
		ft.	in.	ft.	in.
LIAS	Limestones, with dark shales and clays	500	0	500	0
COTHAM BEDS	Marls, green, with red and white patches	18	0	518	0
	Marls, green, passing down to white and green calcareous sandstone	2	0	520	0
UPPER SANDSTONE	Sandstone, pale green and grey, with a few pebbles in the lower part	15	6	535	6
	Sandstone, pale green and grey, fine-grained and shaly, with *Mytilus cloacinus* Tutcher at the base	18	0	553	6
BLACK SHALES	Shales, dark grey, with nodular limestones	2	6	556	0
KEUPER	Limestone conglomerate				

The Rhaetic–Lias junction is marked by a blue-grey, muddy, shelly, detrital limestone which, in one specimen (E.20288), is in contact with green marl. Specimens lower in the bore (E.20289–95) are notable in that they include two of limestone from within the body of the Upper Sandstone. One, from a depth of 531 feet (E.20293), is described by Dr. J. Phemister as 're-crystallised, with quartz, chert, grit and interstitial barytes'. The other (E.20295), may in Dr. Phemister's opinion, have been affected by stress; it was collected at 532 feet, only a foot below the first limestone, but at the same depth as a specimen of coarse, pebbly sandstone. Since the borer's log records 'sandstone with lime ring' between 521 feet and 532 feet 6 inches and 'sandstone with a few pebbles' from 532 feet 6 inches to 535 feet 6 inches it seems likely that the two limestone specimens are from pebbles in the sandstone.

(c) No. 3 Bore

No. 3 Bore (935793), near Coychurch, was sunk in 1937. The following log by the borer is the only record preserved:

		Thickness		Depth	
		ft.	in.	ft.	in.
LIAS	Limestones, with shale and clay partings	140	6	140	6

		Thickness		Depth	
		ft.	in.	ft.	in.
COTHAM BEDS	Marls, red and grey, with limestones, sandy in the lower part	24	11	165	5
UPPER SANDSTONE	Sandstone, hard, grey, with lime and traces of galena	22	11	188	4
	Sandstone, hard, with lime and a little shale	12	3	200	7
? BLACK SHALES	Shales, dark, blue-grey, with lime and shale flake at the top ...	3	3	203	10
KEUPER	Limestone conglomerate				

5. PETROGRAPHIC NOTES ON THE SANDSTONES

The sandstones carry a high percentage of quartz which accounts for their use in the manufacture of refractories. Analyses of specimens from Quarella Quarry (Strahan, 1904, 52) show 91.2% silica whilst some beds at Stormy Down may contain as much as 95%. These figures apply to the middle beds of the Upper Sandstone, but the Lower Sandstone is likely to be almost as siliceous. The flaggy beds at the base of the Upper Sandstone, however, have a high content of clay, whilst the highest of all the sandstones—those underlying Cotham Beds—contain much calcite with subordinate dolomite and barytes.

Thirty specimens from various localities and horizons were crushed, sieved (I.M.M. sieves) and separated through bromoform (S.G. 2.85). The material which passed through 70-mesh and rested on 100-mesh (0.13–0.18 mm.) yielded a heavy residue ranging from 0.02% to 0.60%. These figures, however, are a measure of the content of fossil phosphate (p. 173) rather than the heavy mineral suite. The latter is fully represented only in separations of sand passing through 100-mesh sieves. The following minerals are identified:

CUBIC	TETRAGONAL	HEXAGONAL	ORTHORHOMBIC	MONOCLINIC
Garnet	Zircon	Quartz	Topaz	Muscovite
Magnetite	Rutile	Apatite		Orthoclase
		Tourmaline		Chlorite
		Haematite		

(*i*) *Garnet*. Colourless and pink garnets are the most common, though red forms also are seen in the Lower Sandstone. Most specimens are strongly etched and anhedral, though a few dodecahedra occur in the Upper Sandstone.

(*ii*) *Magnetite*. No special features are observed in the magnetite, which is usually associated with haematite.

(*iii*) *Zircon*. Both colourless and purple zircons occur, the more strongly coloured forms showing faint pleochroism. In the flaggy beds at the base of the Upper Sandstone euhedra are common; some show the forms (100)(111)(110) whilst others, less common, form stumpy prisms or are elongated parallel to the c axis to become spindle-shaped, or even acicular. In the other beds, however, zircon occurs mainly as rounded prisms.

(*iv*) *Rutile*. Rutile occurs mainly in well-rounded prisms varying in colour from pale brown to deep red. In the flaggy beds of the Upper Sandstone pale yellow idiomorphs are abundant. Some show polysynthetic twinning in lamellae parallel to (101), others, less common, show geniculate twinning on (101) and (301).

(*v*) *Quartz*. Quartz is found in sub-angular to sub-rounded grains, some displaying undulose extinction. In general, they contain an abundance of fluid and mineral inclusions. In some grains the latter consist of specks of opaque, black material, possibly magnetite; in others, the inclusions range in size from 0.005 to 0.07 mm. and include tourmaline, zircon and deep red rutile. Other acicular inclusions may be apatite whilst a green chloritic mineral—perhaps prochlorite—is also common.

(*vi*) *Apatite*. Apatite occurs usually as colourless, rounded prisms; some are clear but most are dusky and clouded by fine, dark inclusions. The mineral occurs in all but the fine, flaggy sandstones; it is mainly sparse in distribution though abundant in a specimen from the Quarella Quarry at Bridgend.

(*vii*) *Tourmaline*. Tourmaline is the most abundant heavy mineral of the suite. The common colours are pink, brown and blue but yellow and pale green varieties also occur. A few specimens show a patchy blue and brown colouring. Some blue grains are so dark as to be almost opaque; they have vertical growth striation and basal cleavage with emerging optic axes. Good idiomorphs occur on all sandstone horizons but rounded, stumpy prisms are the usual forms.

(*viii*) *Topaz*. Topaz occurs, in small quantities throughout the sandstones, as rounded or sub-angular fragments showing good basal cleavage. Fluid inclusions are seen in some, but most grains are clear.

(*ix*) *Orthoclase*. Orthoclase is relatively scarce and is sporadic in distribution. Fragments are usually part-altered and worn.

(*x*) *Muscovite*. Muscovite is most abundant in the flaggy beds at the base of the Upper Sandstone, though it is also found, sparingly, at other horizons. It occurs in colourless flakes showing slight alteration.

(*xi*) *Chlorite*. Like muscovite, chlorite is most common in the base of the Upper Sandstone. Most specimens are green, but these are frequently edged with yellow. Varieties also occur which are entirely yellow or brown in colour. N_m is 1.62.

(*xii*) *Haematite*. Haematite is frequently seen as a rim to magnetite. It also forms powdery aggregates and may coat grains of quartz or mica. Some minutely botryoidal haematite also occurs.

The mineral assemblage of the flaggy beds at the top of the Upper Sandstone is easily distinguished from those of the other sandstones by grain size (0.025–1.0 mm.), abundance of clay, muscovite and idiomorphic (perhaps authigenic) rutile and by an almost complete lack of garnet. In the other beds, by contrast, clay and muscovite are rare, rutile occurs in rounded, red or brown prisms and garnet is common. Garnet is so abundant in the Lower Sandstone as to be almost diagnostic though the heavy mineral suite is otherwise like that of the middle, much-quarried part of the Upper Sandstone.

There is a broad resemblance between the heavy minerals of the Rhaetic and those of the Old Red Sandstone of the Cardiff district (Heard & Davies, 1924), the Coal Measures near Swansea (Stuart, 1928) and the Culm of NW. Devon (Stuart & Simpson, 1934). On the other hand, the Rhaetic suite seems markedly different from that of the Pennant Series east of the River Taff (Heard, 1922). The evidence tends to confirm the previous suggestion (Pringle & George, 1948, 85) that the Rhaetic sandstones were derived from Millstone Grit and Coal Measures to the north.

6. FOSSIL PHOSPHATE

Fossil phosphate, all in small particles, is most abundant at the tops and bottoms of the Upper and Lower sandstones though it also occurs on other, intermediate horizons. It is mainly yellow or brown in the Lower Sandstone, but colourless or pale grey with subordinate yellow in the Upper Sandstone. The difference in colour supplements the heavy mineral assemblage as a means of distinguishing between the two sandstones. The phosphate shows an apparent wide range of specific gravity since it appears in light and heavy fractions passed through bromoform (S.G. 2.85) and Klein Solution (S.G. 3.36). Some of it is isotropic, but more commonly it displays undulose extinction which is probably caused by internal structure. The refractive index has a range (1.61 to 1.64) comparable with that of collophane. Most of the phosphate is shapeless, but some fragments are clearly organic. The material has been examined by Dr. John Griffith who has kindly reported as follows:

'The recognisable organic remains appear to consist to a large extent of small fish-teeth. These are usually broken, but I have been able to find two or three intact specimens (Plate 3 A and Fig. 2). The teeth show considerable variation in proportion, but, so far as I can see, are all of one kind, i.e. probably belong to one species of fish. The intact teeth consist of an almost cylindrical basal portion of dentine and a roughly conical apical cap of enamel. The basal portion (Plate 3 B–C) is slightly greater in diameter near the tooth base than at its junction with the enamel cap; it is pierced by a tapering pulp cavity and from this the dentine tubules arise. These run for the most part approximately at right angles to the longitudinal axis of the pulp cavity but near its blind end lie at a more acute angle and reaching the dentino-enamel junction. The enamel cap (Plate 3 D–G) is approximately conical in shape but tends to be curved, especially in teeth where the height of the cap is great relative to its diameter at the junction with the basal portion of the tooth. The enamel contains a number of fine tubules directed from near the centre of the cap base towards its outer surface. The pulp cavity does not, as a rule, extend any appreciable distance into the part of the tooth covered by the enamel cap. Accurate specific identification is impossible owing to the fragmentary nature and small size of the remains, especially as the identity of some of the larger teeth from the Rhaetic shales is by no means clear. Nevertheless the specimens show a certain similarity to some of these teeth belonging to the genus *Saurichthys* and I think they can reasonably be identified as cf. *Saurichthys*.

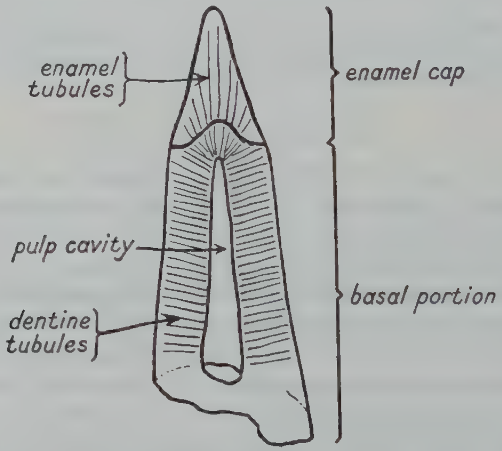
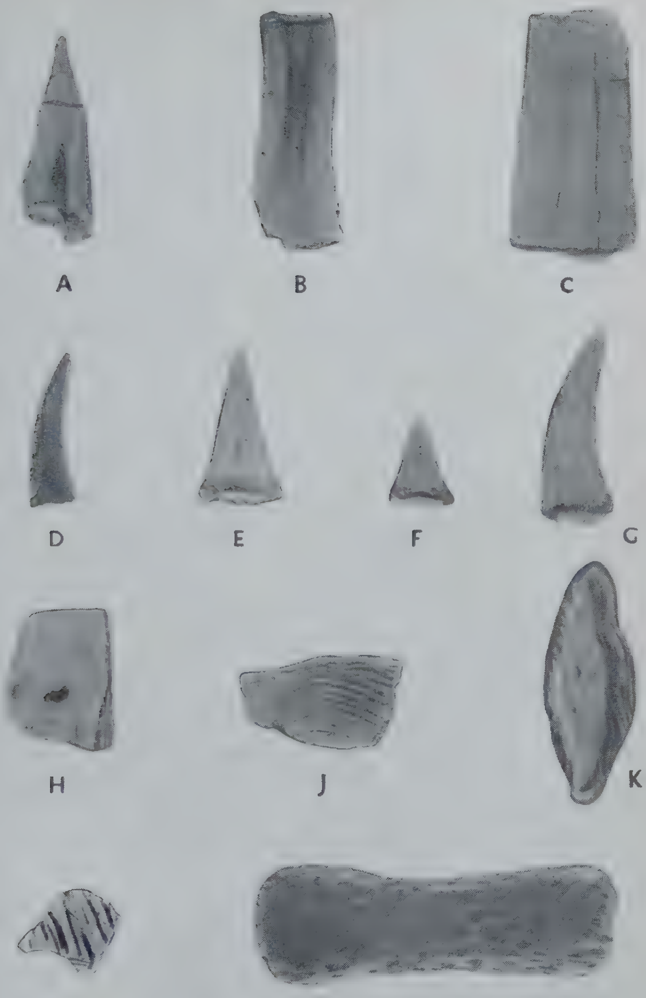


Fig. 2. Sketch of complete fish-tooth (see also Plate 3 A)

The other remains appear to consist mainly of fragments of fish-scale (Plate 3 H–K). Here no specific identification is possible as none of the fragments is anything like complete. However, the only fish-scales recorded from the Rhaetic shales have been attributed to the genus *Gyrolepis* and it is possible therefore that the fragments may belong to this genus.

One specimen (Plate 3 L) is almost certainly a small piece of dentine as parallel dentine tubules with a few finer side branches are visible. Judging by the size and arrangement of the tubules and their side branches I should

PLATE 3



[*To face p.* 174

say that it was probably part of an Elasmobranch tooth (cf. *Acrodus, Hybodus* from the Rhaetic shales).

Another specimen (Plate 3 M) is undoubtedly a small piece of bone as its finer structure is unmistakable. It is almost certainly either fish or reptilian.'

7. CONCLUSIONS

(a) Correlation

The Lower Sandstone, where present, rests with unconformity on Keuper and its base forms a natural lower limit for the Rhaetic in the Bridgend district. There is no certain way of correlating this unconformity with those occurring at, or just below, the base of the Rhaetic in the Cardiff district (Miskin, 1918, 23, 24). Thus the Lower Sandstone may be the equivalent of either the fossiliferous upper portion of the Grey Marls (Richardson's Sully Beds) or the lowest Westbury Beds. The Black Shales and Upper Sandstone are correlated more certainly with the upper part of the Westbury Beds. It is probable that the detrital limestones of Sutton Stone affinity occur on at least two horizons within the Cotham Beds. The lower, described by Strahan at Melin Cwcw, is white like the lower part of the marls, but unlike the blue-grey rock found at a higher horizon, near the top of the marls, east of Pyle. The latter may be at, or about, the horizon of the detrital limestones in No. 2 Bore. The apparent absence, at all but one locality, of the topmost shales of the Cotham Beds indicates minor unconformity at the base of the Lias.

(b) Littoral Deposits

Strahan (1904, fig. 2, 24) showed that there was, in the Triassic sea, a large island aligned along an east–west line corresponding to the axis of the pre-Triassic Cowbridge–Cardiff Anticline. Its northern shore-line now forms a natural southern margin to the Bridgend district of this account. Rocks of Keuper and Rhaetic age were thought to have been banked against the island with successive overlap and with local formation of littoral deposits until, in Lower Lias times, the island became completely submerged. This would account for the overlap of Lower Sandstone by Upper to the east of Bridgend (Fig. 3) and also for the overlap of Lower Rhaetic Beds by Upper Rhaetic Beds as indicated by the virtual absence of the former in the fissure in Carboniferous Limestone at Stormy Down.

The depositional history is made more complex, however, by contemporaneous movement along the axis of the anticline as recognised by Richardson (1905, 411). Uplift and erosion explain the presence of fragments of Tea Green Marls in the Upper Sandstone at Stormy Down and also the reappearance of sandstones south of the island and its associated littoral deposits. The same processes may also explain why the detrital

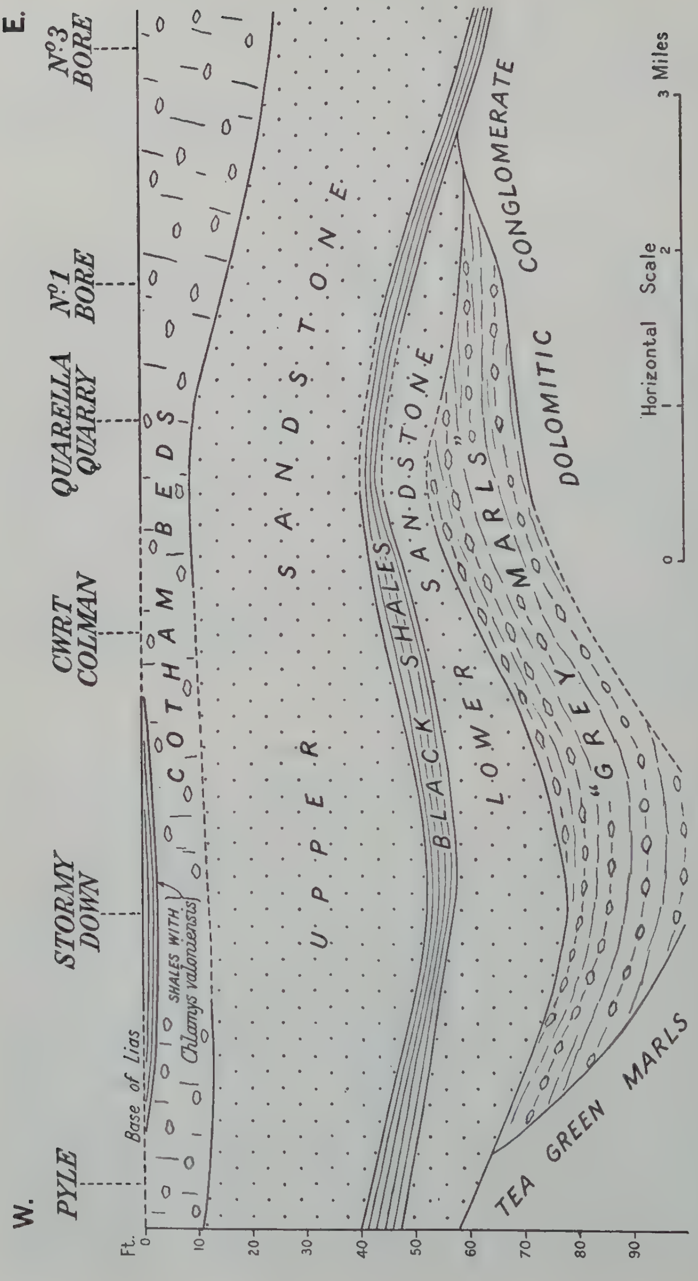


Fig. 3. Diagram to illustrate lateral variations and unconformities in the Rhaetic

limestones like Sutton Stone, which appear within the Cotham Beds and in the lower part of the Lias, extend well beyond the margins of the island.

It is notable that the Cotham Beds are the only Rhaetic sub-division in which this type of littoral rock occurs. The near-shore equivalents of the sandstones appear to be coarse, pebbly grits like those in No. 2 Bore and at Stormy Down, or sandstone conglomerates as at Tythegston.

(c) Transition from Sandstone to Shale

From the exposures to the south-east of Cowbridge (p. 168) it would seem that the twofold subdivision of the sandstones persists for some distance beyond the contemporary island and its associated littoral deposits. It is suggested, therefore, that, as a transitional stage, the sandstones first become finer grained and interdigitated with the black shales before being entirely replaced by them in the district around Cardiff. The interdigitation is envisaged as an alternation of wedges of sandstone and shale similar to that described by George (1937, 121) at Dunhampstead.

This interpretation differs from that of Strahan & Cantrill (1904, 35, 43, 50), who thought that the transition between sandstone and black shales was represented by the sandy oolites which crop out in the railway-cuttings at Cowbridge and St. Mary Church Road Station (Cantrill, 1904, 41–9). These localities border on the southern shore-line of the contemporaneous island and it is now thought more likely that the oolites are Upper Rhaetic littoral rocks containing sand derived from erosion of Lower Rhaetic sandstones.

ACKNOWLEDGMENTS

The author wishes to record his thanks to the Director of the Geological Survey for permission to publish records of borings. Mr. R. V. Melville has been particularly helpful in determining material collected at the bores and elsewhere, and Dr. John Griffith has contributed a valuable report on the fossil phosphate. Grateful acknowledgment is made of assistance from Professor T. N. George who first suggested the work and the late Professor Duncan Leitch and Messrs. Brian Simpson and T. R. Owen under whose guidance, at University College, Swansea, most of it was done. Others to whom the author owes thanks for critical reading of the manuscript are Drs. G. H. Mitchell and A. W. Woodland and Messrs. J. Knox and R. I. Cook.

EXPLANATION OF PLATE 3

Photomicrographs of fossil phosphate from Lower Rhaetic sandstones, P.P.L. (×100). Determinations by Dr. John Griffith.

Numbers preceded by PF refer to slides in the Geological Survey collection.

A. Complete small fish-tooth cf. *Saurichthys*. Near base of Upper Sandstone, Quarella Quarry, Bridgend (PF 666).

B–C. Detached basal portions of small fish-teeth cf. *Saurichthys.* Both from base of Lower Sandstone. B from old quarry 400 yards south of old lime works, Stormy Down (PF 671); C from road-cutting west of Pyle Railway Station (PF 672).

D–G. Detached enamel caps of small fish-teeth cf. *Saurichthys.* D from ? Upper Sandstone, The Cross, St. Hilary (PF 665); E and F from near base of Upper Sandstone, Quarella Quarry, Bridgend (PF 666); G from top of Upper Sandstone, old quarry behind St. James's Church, Pyle (PF 668).

H–K. Fragments of fish-scale cf. *Gyrolepis.* H from top of Upper Sandstone, old quarry behind St. James's Church, Pyle (PF 668); J from top of Upper Sandstone, stream one and a half mile east of Pyle (PF 669); K from base of Lower Sandstone, old quarry, 400 yards south of old lime works, Stormy Down (PF 671).

L. Fragment of dentine, probably part of an Elasmobranch tooth. Base of Upper Sandstone, old quarry behind St. James's Church, Pyle (PF 667).

M. Fragment of bone. Top of Lower Sandstone, railway-cutting, Cwrt Colman (PF 670).

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Some Observations on the Antrim Basalts and Associated Dolerite Intrusions

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ABSTRACT: The work embodies miscellaneous observations on the general structural characters of the Tertiary basalt lavas and minor intrusions of north-eastern Ireland. Individual lava flows are found to average twenty-two feet in thickness, the thickest reaching 150 feet. Certain flows can be traced horizontally for as much as six miles. Basalt pegmatites are described which bear sodalite, a mineral new to Ireland.

Composite lava flows are recorded for the first time in Ireland. Several examples have been located, and in each the components, separated by a sharp but unchilled contact, are of olivine–basalt and picrite–basalt respectively. The lavas are associated with a swarm of dykes and one, possibly two, dykes are now known to be the feeders of lava flows. Dolerite plugs may also represent the feeders to lava flows.

Six newly discovered plugs are recorded, bringing the total number known to around thirty. The Donegore dyke, formerly regarded as a broad dyke, is re-interpreted as a string of four small plugs.

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1. INTRODUCTION

TERTIARY BASALT lavas occupy an area of some 1500 square miles in Antrim and adjacent counties in the north-east of Ireland. Excellent accounts of the general characters of the Antrim Basalts are given by Geikie (1897) and Charlesworth (1935), and a considerable amount of detailed work has been done since then, especially by Tomkeieff & Patterson, as listed in the bibliography, but certain aspects of the Antrim plateau still lack adequate description.

The present work stems from incidental observations made during a regional study of the amygdale-minerals in the lavas, observations on the general structural characters of the lavas and such small-scale features as auto-intrusions. Several composite lava flows, the first to be recorded in Ireland, have been found, and new evidence bearing on the mode of eruption of the basalts includes the discovery of a lava flow connected to its dyke-feeder. In addition to the dykes there are numerous dolerite plugs that have also probably contributed to the lava pile, and during the course of the field work six new plugs have been located and are placed on record for the first time, bringing the total number of plugs known to about thirty.

The volcanic succession consists almost entirely of basalt lavas, although acid rocks occupy a few square miles of country on and around Tardree Hill and in several small patches elsewhere. Detrital beds of any kind are decidedly rare, and bedded pyroclastic rocks are developed on a considerable scale only in the vicinity of the Carrickarede volcano on the north coast of Antrim. Sedimentary beds are practically confined to the interbasaltic horizon, a prominent zone of weathering (Cole, 1912; Eyles, 1952) which over most of Antrim divides the lavas into two series, the Lower Basalts and the Upper Basalts. A threefold succession has recently been established by Patterson (1955a), in the north of Antrim, where there are two such zones of weathering.

The lavas rest upon an eroded surface of Chalk, often with small solution pits and swallow-holes, and there is a thin intervening bed of clay-with-flints, often red and lateritic and occasionally with plant remains at the top of the clay. Cleland (1928, 1930, 1933) has described from Magheramorne and Whitehead a thin bed of redeposited detrital chalk above this clay. Near Donald's Hill the writer has observed silicification of the top of the clay.

It has long been regarded as established that the lavas are the product of subaerial eruptions, from the absence of pillow-lavas and of intercalated marine sediments and marine fossils, and from the presence of occasional plant beds in the succession. The tops of the lava flows are typically red, probably mainly by contemporaneous lateritic weathering. The interbasaltic horizon (Cole, 1912; Eyles, 1952), with its lateritic iron ores and bauxites which have been mined from time to time, is such a zone of weathering of unusual thickness representing a lull of considerable duration between the outpouring of lavas. Detrital (dust) partings of the type described from Iceland by Hawkes (1916) are apparently very seldom developed.

Apart from a group of tholeiite flows developed in the north of Antrim (the Middle Basalts of Patterson, 1955), which attain an aggregate thickness of several hundred feet and include the famous columnar flows of the Giant's Causeway (Tomkeieff, 1940b), virtually the whole of the Antrim Basalts are olivine-basalts (Tomkeieff, 1934) of rather uniform character. They are often rather rich in olivine (20% or more in the mode) and grade into picrite-basalts.

The original thickness of the lava pile is not known. In the Garron Plateau and in places along the western escarpment up to 1000 feet of lavas are exposed for study, but there is no means of telling what thickness has been eroded away. The Aughrimderg borehole in the Coalisland area passed through 990 feet of basalts, and Hartley (1948) estimated that the total thickness of lavas there is about 1600 feet. The Langford Lodge Borehole (Fowler, 1957) passed through 2590 feet of basalts.

The lavas are disposed in the form of a very shallow, boat-like trough with axis pitching towards the south-west, and the base of the lavas attains

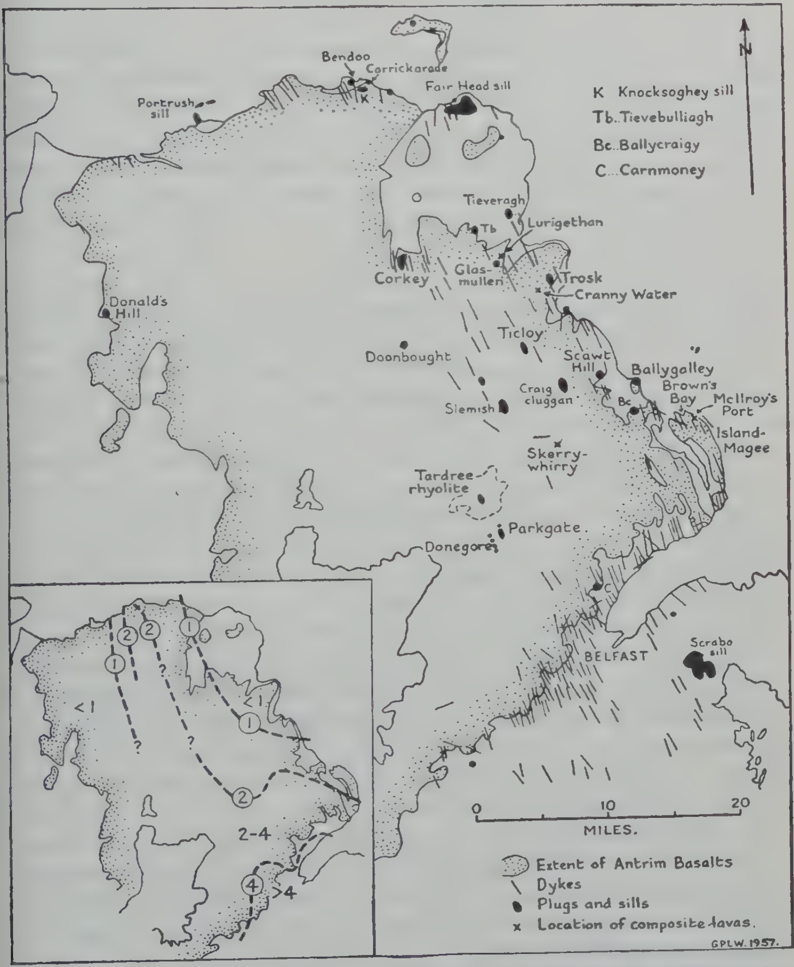

Fig. 1. Sketch-map of the Antrim Basalts showing the distribution of dykes and other intrusions and the location of composite lava flows. Inset map shows tentatively the intensity of the dyke swarm, expressed as percentage stretch

its greatest known depth (2700 feet below sea-level suggested by Hartley, 1948) in the south-west in the Coalisland area. At the other extreme the base of the lavas attains in places an altitude of well over 1000 feet along the prominent escarpments which bound the basalt plateau on the east and west.

2. STRUCTURAL CHARACTERS OF THE LAVAS

Geikie (1897, 202) estimated the average thickness of the constituent lava flows in the Lower Basalts as fifteen feet. The 106 basalt flows measured by the writer at Islandmagee, Agnew's Hill, the Garron Plateau, the Giant's Causeway and in the mountains west of Belfast have an aggregate thickness of 2450 feet, giving an average thickness of twenty-three feet. This compares with the average of twenty-one feet for 109 flows in other parts of the Antrim Basalts from values recorded in the literature (Washing Bay bore, Wright, 1924; Aughrimderg bore, Hartley, 1948; Binevenagh, Slieve Gullion and Downhill, Patterson, 1955b, Hospers & Charlesworth, 1954).

Apart from a tendency for the flows of tholeiite to be thicker than those of olivine-basalt, there is little correlation between thickness of flows and composition of the rock. In general, however, the thinner the flow the coarser the rock, both being a function of the fluidity of the lava. The two most coarse-grained flows seen, of doleritic grain-size, each have a thickness of only ten feet, which is well below the average.

The thickest flow known to the writer is an olivine-basalt flow exposed on the Black Mountain west of Belfast. It attains a thickness of 150 feet. Several other flows have been found elsewhere with a thickness of about 100 feet.

It is seldom possible to trace a flow far on account of the usual lack of distinctive characters and the inadequacy of the exposures in most areas, but the following observations have been made:

A. A distinctive flow with sparse large feldspar phenocrysts is seen about 300 feet up in the lavas along the northern edge of the Garron Plateau, and has been traced continuously from the Inver River to near Garron Point, a distance of six miles. In this distance the thickness varies from sixty to eighty feet. Probably the same flow is seen again in the Cranny Water, four miles south of Garron Point.

B. On the Black Mountain, west of Belfast, a very thick flow (in places 150 feet thick) of olivine-rich basalt can be traced from Whiterock to Hannahstown, a distance of three miles. If, as seems likely, a flow with similar characters on Cave Hill is the same flow, the lateral spread is increased to six miles.

C. Three flows of olivine-rich basalt, fairly distinctive in the field and well exposed in a large number of quarries, can each be traced without difficulty from the White Mountain to Collin Glen, a distance of nearly four miles.

D. At the other extreme, a flow (continuous with its dyke-feeder) on the eastern shore of Brown's Bay, Islandmagee, has a lateral extent in the cliff section of only seventy feet, and attains a maximum thickness of ten feet. Other examples of flows and pahoehoe flow-units thinning out within a short distance are common around the coast of Islandmagee.

(a) Small-Scale Structures

Typically the uppermost quarter to a half of a lava flow is highly amygdaloidal. In addition there is a thin layer of amygdaloidal rock at the base. The amygdales are usually not more than several inches in diameter but exceptionally exceed one foot. Pipe amygdales are found in a large proportion of the flows, and are of two distinct types. Firstly there are the short pipes, found at the base of thin flows or flow-units of pahoehoe; they are usually about six inches long and quarter to half an inch in diameter, and two often coalesce upwards in an inverted Y. Secondly there are the long pipes which extend from bottom to top of a flow; they are about two inches in diameter but are usually pipe-like trains of small amygdales rather than continuous pipes, as illustrated by Shrock (1948, fig. 314).

The amygdales contain zeolites and other secondary minerals, namely calcite, aragonite, apophyllite, gyrolite, chalcedony, quartz, opal and mineraloids such as chlorophaeite. Empty vesicles are uncommon. The amygdale-minerals have a regular distribution which can be, and has been, mapped (Walker, 1951) and it is clear that the great bulk of them have crystallised very late in the volcanic history of the area.

Flow structures include occasional bending-over of short pipe-amygdales; the streaking-out of clusters of amygdales into bands which may alternate with bands of non-amygdaloidal rock; horizontal elongation of amygdales, in particular those in the interior of a flow; and parallel orientation of the tiny feldspar tablets in the more fine-grained basalts, usually resulting in a platy jointing. Many of the more fine-grained and olivine-rich basalts, such as are common on the higher ground in the east of Antrim, have a streaky flow-banding, well shown on weathered surfaces, with bands half an inch or so thick of slightly differing grain-size. The flow-banding is usually more or less parallel to the margins, but near the base of a flow it may be folded and contorted. Also indicative of flow is the occasional streaking-out of basalt pegmatites or bands of different rock-types, as exemplified by the composite lava flows (Fig. 5).

The best exposures for the study of the structure of lava flows are those along the sea coast of Islandmagee, and numerous examples have been found there of the uncovering of the ropy tops of flows of pahoehoe, one very accessible exposure being on the eastern shore of Ferris Bay. Cracks in the top of pahoehoe flows are often seen infilled from above with lateritic weathering products or later basalt. Aa is much less commonly seen than pahoehoe.

Columnar jointing is well developed only in the group of tholeiite flows along the north coast of Antrim (Tomkeieff, 1940b). Composition of the rock alone does not determine the nature of the jointing, for columnar jointing is also known in olivine-basalts, such as the basal flow in the main quarry at Whitehead and in a quarry on the western side of Muldersleigh Hill, north of Whitehead. It is also seen in a flow practically at the base of the lavas in the vicinity of Garron Point and again (if the flow is the same one) in a quarry on the west side of Glen Ballyemon. These occurrences of columnar flows at the base of a lava series, where they rest upon an eroded surface, may be significant. The writer considers that columnar jointing results when a lava is ponded in a surface depression, although it does not seem possible in Antrim to demonstrate decisively that this is so.

(b) Auto-Intrusions and Basalt Pegmatites

The phenomenon of auto-intrusion is comparatively seldom seen. One of the best examples is exposed in the coastal cliffs near the two-mouthed cave south-east of Portmuck, Islandmagee. The parent flow is a picrite-basalt[1] forty feet thick, and near the middle is a thin sheet of basalt much poorer in olivine and coarser in grain, and in composition corresponding roughly to the groundmass of the picrite-basalt. The two rocks are separated by a sharp but unchilled contact. This sheet can be traced laterally, varying in thickness from seventeen to twenty inches, for 400 feet before exposures fail. At one end the sheet descends abruptly in the lava, although unfortunately the base of the flow is below sea-level here; at this point, too, there is a vertical offshoot which gives off a number of thin sheets, as illustrated by the drawing, Fig. 2 a.

The field relations show clearly that the sheets were formed when the flow was still hot, and their great lateral extent indicates that the lava was still moving at that time, although perhaps in a very pasty condition, and one must suppose that the sheets obtained their material by squeezing-out from other more fluid parts of the flow.

Basalt lavas may have pegmatites, in the same way that granites may have associated pegmatites. Basalt pegmatites are characteristically somewhat coarser in grain than the parent basalt, and the contact is sharp and firmly welded but without any sign of chilling. The texture of the pegmatites is dominated by prismatic to subophitic titanaugite crystals several millimetres long, that are sometimes rimmed by a little aegirine-augite or aegirine. Associated with it are thin plates of ilmenite about the same size, strongly zoned medium or sodic plagioclase feldspar, and an abundance of zeolites in amygdales, in the groundmass of the rock, and replacing the plagioclase, together with accessory apatite as long, slender needles. The pegmatites are usually olivine-free, but when olivine does occur it is more fayalitic than in the basalts. Chemically the basalt pegmatites must show an enrichment in titanium, sodium, water and perhaps iron as compared with the basalts.

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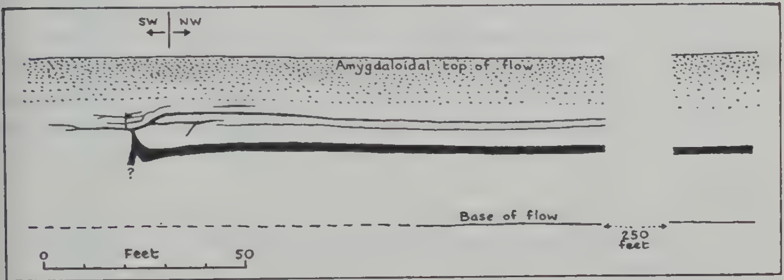
[1] The term picrite-basalt is applied here to those olivine-basalts which contain 30% or more by volume of modal olivine.



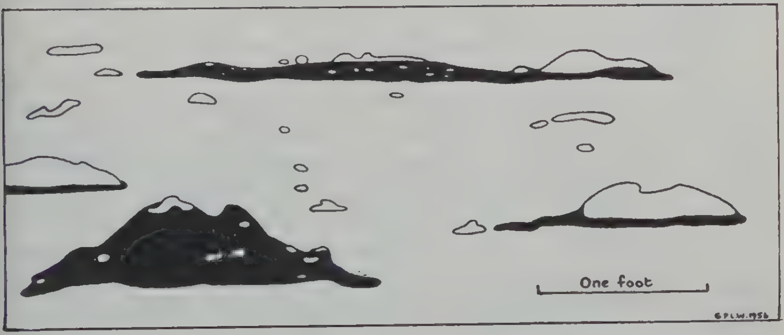


Fig. 2a. (above). Auto-intrusions in lava flow seen in section on coast south-east of Portmuck, Islandmagee

b. (below). Section showing basalt-pegmatite (black) associated with and flooring large amygdales in olivine-basalt. Coast west of Whitepark Bay

A small amount of basalt pegmatite is found in many olivine-basalt flows, as irregular veinlets, up to several inches thick; as planar sheets that exceptionally extend laterally for as much as 100 feet; as small patches intimately associated with amygdales (Fig. 2 b); and as vertical pipes forming the matrix of pipe-amygdale trains. Probably the pegmatite, which crystallised in a gas-rich environment, is derived by differentiation from the basalt in which it occurs, and the genetic relationship is similar to that between granite pegmatite and the granite in which it occurs.

(c) Alkaline Pegmatites

Quite unique, yet clearly closely related to the normal pegmatites in the basalts, are the feldspathoid-bearing pegmatites found in the lower component of the McIlroy's Port composite lava flow, Islandmagee, described on a later page. Mineralogically they are pyroxenites containing sodalite, the first record of this mineral in Ireland.

These pegmatites form irregular patches or veins up to two inches thick and are confined to a zone one foot thick (Fig. 4) in the olivine-rich basalt comprising the lower part of the flow. Adjacent to them the basalt itself has been converted into a rock with granular aegirine-augite enclosed by poikilitic plagioclase and sodalite, and a few relics of iddingsite are all that remains of the original olivine plenocrysts. The pegmatites are in sharp but unchilled contact with this altered basalt, and the basalt has been embayed by them and contains a notable concentration of magnetite along the contact.

There is an indication, from the symmetrical distribution of rock-units in the lava flow (Fig. 3), that the orifice of eruption is very close at hand, and the pegmatites appear to represent the final dregs of volatile-rich magma to be erupted.

The most melanocratic pegmatites (Fig. 9) contain more than 70% of titanaugite, with 10 to 20% of interstitial sodalite and minor amounts of medium plagioclase and magnetite, with accessory apatite and occasional relics of olivine replaced by iddingsite. The sodalite has a trellis of minute opaque inclusions. The least melanocratic pegmatites contain around 50% of deeply coloured and strongly zoned aegirine-augite, idiomorphic rhombdodecahedral sodalite, plagioclase and accessory apatite and magnetite. There is a continuous gradation between these extremes, and the more melanocratic pegmatite often rims patches of less melanocratic nature. The feldspathoid is sometimes perfectly fresh, and its identity has been confirmed by its X-ray powder pattern, but more often it shows varying degrees of alteration to zeolites.

Thin sections of these pegmatites occasionally show a marked concentration of sodalite, which may constitute up to 60% of the rock, and apatite, which may constitute up to 50% as large, stumpy euhedral crystals. Closely related to these pegmatites are bands of magnetite-aegirine augite rock which cut the basalt in one place. The feldspathoid-bearing pegmatites pass into normal basalt pegmatites composed essentially of plagioclase and titanaugite.

Chemical analyses of two specimens of pegmatite and of the enclosing picrite-basalt are presented in Table I, 1, 2 and 3. As compared with the picrite-basalt the pegmatites have a much lower content of silica and magnesia and show significant enrichment in lime and titania and higher state of oxidation of the iron.

TABLE I. **Chemical Analyses**

	1	2	3	4	5
SiO_2	40.71	39.26	45.67	42.6	45.7
TiO_2	2.38	1.25	.76	.67	1.3
Al_2O_3	12.75	18.33	13.46	9.6	16.8
Cr_2O_3	—	—	.31	—	—
Fe_2O_3	6.12	6.29	1.33	2.4	1.8
FeO	5.55	1.97	8.65	10.0	9.2
MnO	.29	.32	.18	.16	.15
MgO	9.77	7.24	16.30	22.8	9.6
CaO	18.56	15.58	9.74	5.7	10.5
Na_2O	1.71	3.26	1.53	1.2	2.5
K_2O	.01	.35	.14	.25	.27
P_2O_5	.13	.22	.11	.06	.12
H_2O^+	1.78	4.55	.87	4.0	1.4
H_2O^-	.07	.99	.39	—	—
CO_2	.15	.36	—	—	—
F	—	tr.	—	—	—
Cl	—	.37	—	—	—
SO_4	—	tr.	—	—	—
	100.01	99.86	99.54	99.4	99.3
D	—	—	—	2.93	2.97

1. Titanaugite pyroxenite pegmatite with sodalite, south of vent, McIlroy's Port, Islandmagee. Analyst: M. H. Kerr.

2. Aegirine-augite pegmatite rich in sodalite, same locality. Analyst: M. H. Kerr.

3. Picritic olivine-basalt, lower component of McIloy's Port composite lava flow, just south of vent. Analyst: M. H. Kerr. Modal analysis, Table II, 1b.

4. Picrite-basalt, lower component of composite lava flow, Cranny Water, Carnlough. Analyst: P. J. Curtis. Modal analysis, Table II, 2a.

5. Olivine-basalt layer in composite lava flow, Cranny Water, Carnlough. Analyst: P. J. Curtis. Modal analysis, Table II, 2b.

(Analyses 4 and 5 by methods based on Shapiro & Brannock, as modified at Imperial College.)

3. COMPOSITE LAVA FLOWS

A number of examples are known in Antrim of lava flows made of two rock-types, namely olivine-rich basalt (picrite-basalt) and relatively olivine-poor basalt. For some, Tomkeieff (1934) has ascribed this to gravity-settling of olivine crystals in place. In others, however, there is a sharp contact between the two rock-types and the conditions attached by Kennedy (1931) to the definition of a composite lava flow are satisfied, namely that the flow consists of two readily recognisable rock-types, arranged asymmetrically, unchilled against one another, and without any intervening slag. Composite lava flows have not hitherto been recorded from Ireland.

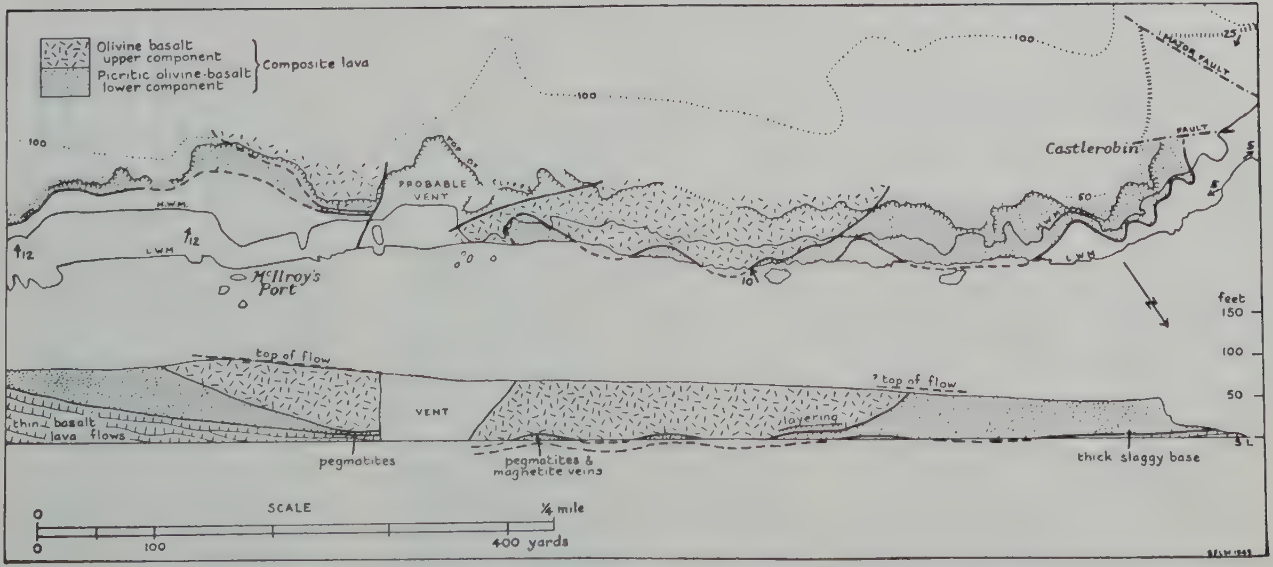


Fig. 3. Map and section of the McIlroy's Port composite lava flow, Islandmagee

(a) McIlroy's Port Composite Flow

This composite flow, the best example known, is almost continuously exposed along two-thirds of a mile of the coastal cliffs (Fig. 3) on either side of the little bay of McIlroy's Port in north Islandmagee. In the centre of the exposure, near where the flow is cut by a probable explosion vent, the flow is composite with an upper component some fifty feet thick of olivine-basalt and a lower, ten feet thick, of rock much richer in olivine and near picrite-basalt in composition. Near the vent this lower component bears pegmatites containing sodalite, as described above.

Southward from the vent the thickness of the lower component increases to 40 feet in little over 100 yards, and the position of the slaggy top of the flow indicates that the upper component has decreased in thickness by a like amount and in all probability comes to an end a short distance farther south, although the flow caps the cliffs, and the top of it is not seen.

To a distance of 200 yards northwards from the vent the coastal cliffs, 50 feet high, are almost entirely made of the upper component of the flow, but farther north it rapidly decreases in thickness, the lower component increasing at the same time to form, with its thick basal layer of slag, the entire mass of the headland east of Castlerobin Bay, beyond which the flow is faulted to below sea-level.

The contacts between the components of the flow are always perfectly sharp and clean-cut. There is no intervening slag or chilling and there is no evidence, in the form of intrusive offshoots, of any intrusive relationships. In places, and especially just south of the vent, the contact is marked by a layer two millimetres thick of augite crystals (Fig. 9). The contact relations are best studied in this cliff-section (Fig. 4), although the actual contact is at first difficult to locate in view of the complete absence of any difference in jointing or resistance to weathering of the two rocks.

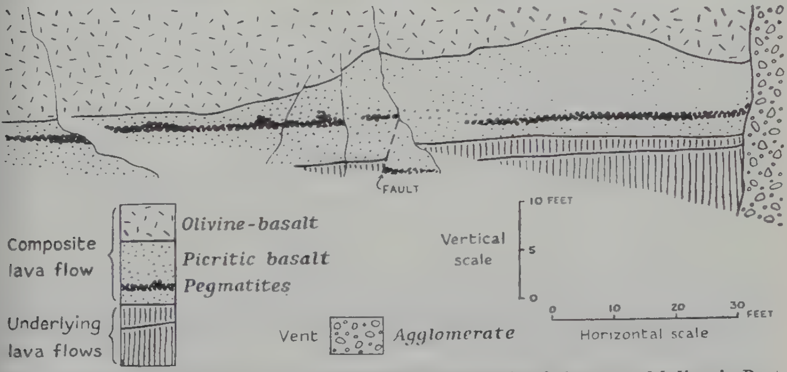


Fig. 4. Contact relations seen in cliff-section just south of the vent, McIlroy's Port composite lava flow, Islandmagee

The lower component of the McIlroy's Port flow is an olivine-rich basalt or picrite-basalt with corroded phenocrysts of olivine up to three millimetres making up some 30% of the volume of the rock. The groundmass is very fine-grained and consists of labradorite and pale brown augite in roughly equal amounts, together with a little olivine and magnetite. The rock is often markedly streaky, with an alternation of bands an inch or so thick in which the groundmass varies in grain-size. Some bands contain minute vesicles.

The upper component of the flow is a coarse-grained olivine-basalt with strongly zoned plagioclase, olivine in ragged micro-phenocrysts that are usually altered to bowlingite, chlorite or iddingsite, and granular pyroxene, together with occasional ill-formed micro-phenocrysts of augite. The pyroxene in the flow is a normal titanaugite with $2V_\gamma = 48$–$54°$ and $\beta =$ about 1.690, but in the upper component there is also a little pigeonite with $2V_\gamma = 10$–$20°$ and with the optic axial plane parallel to 010. One crystal was seen of augite mantled by pigeonite and separated from it by a sharp contact.

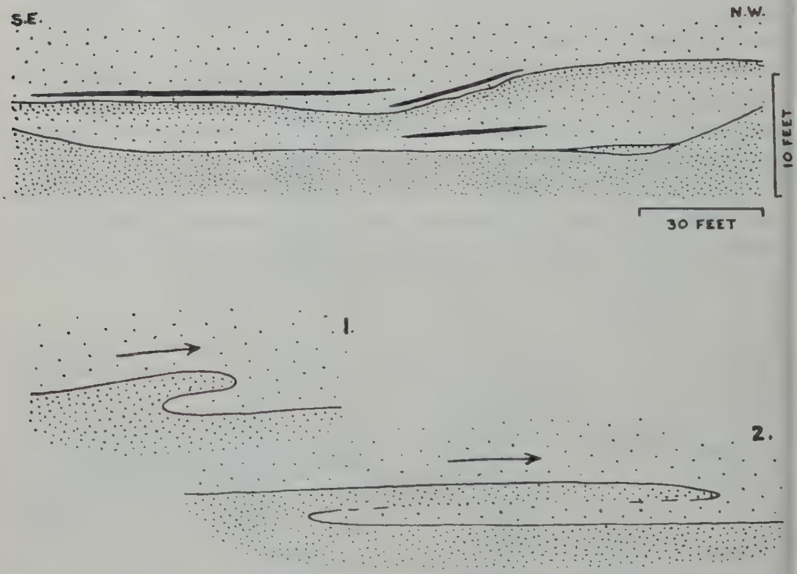


Fig. 5a. (above). Section of part of McIlroy's Port composite flow on the shore midway between the vent and Castlerobin, showing layering. The density of the stippling indicates the content of olivine phenocrysts in the rock. The black bands represent thin sheets of basalt-pegmatite

b. (below). Suggested mechanism of formation of layering, during movement of composite lava

A form of layering is developed in the flow some 200 yards north of the vent. The flow here consists of three or four components, separated by perfectly sharp contacts. The lowest is picrite-basalt, and the highest olivine-basalt, both apparently homogeneous, but between them is a layer of olivine-basalt grading upwards by increase in olivine into picrite-basalt, and at one place there are two such layers, as illustrated by the diagram, Fig. 5. At the same place there are several planar sheets one to two inches thick of basalt pegmatite parallel to the contacts between the components.

It is suggested that the layering at this locality is due to drag-folding and thrusting caused by olivine-basalt magma flowing over picrite-basalt, with intermixing along the 'thrust' to give the observed upward increase in olivine, as presented by the diagrams, Fig. 5 b.

(b) The Lurigethan Composite Flow

A second composite flow is exposed practically at the top of the precipitous escarpment bounding the Glenariff Valley on the west, at the point where a stream has cut a gully, two miles SSW. of Lurigethan summit. The flow is here eighteen to twenty-two feet thick and consists of two components of equal thickness, separated by a sharp but unchilled contact. The lower component is picrite-basalt with about 35% by volume of olivine, and the upper is olivine-basalt with only 15% of olivine, corresponding in composition to the groundmass of the picrite-basalt. Although there are a few amygdales along the contact there is no semblance of an amygdaloidal or slaggy top to the picrite-basalt. That the body is a surface flow and not an intrusion is demonstrated by the presence of pipe-amygdales and of a typical red weathered amygdaloidal top to the olivine-basalt.

An interesting feature of this composite flow is the penetration from bottom to top of the picrite-basalt by long pipe-amygdales which do not, however, enter the olivine-basalt of the upper component. This could be explained were the upper component of more fluid magma than the lower, bubbles from which would rise too rapidly through the upper component to be preserved as pipes. Alternatively the upper component may have been too viscous to permit the passage of bubbles which at the same time were rising through the lower part of the flow, and the sparse amygdales in the picrite-basalt just below the contact may be due to spreading-out of gases which had risen through the pipes.

A second exposure, probably of the same composite lava flow, has been found two miles away in Glenariff Glen, in the path fifty yards above Esse-na-Laragh waterfall. Here the lower component, which is a perfectly fresh picrite-basalt, is about five feet thick, and the upper component, of olivine-basalt, is eight feet thick, the contact between these rock-types being gradational over two inches. Again the lower component is penetrated from bottom to top by long pipe-amygdales which do not, however, enter the upper component.

TABLE II. **Modal Analyses of Composite Lavas**

	1a	1b	2a	2b	3a	3b	4a	4b	5a	6a	6b
Olivine	31	12	45	21	34	14	43	21	35	38	14
Plagioclase	34	54	32	50	32	38	32	49	25	47	55
Augite	33	31[1]	14	25	25	33	13	23	23	12	27
Fe ore	2	3	2	3	3	4	2	2	2	3	4
Zeolites Chlorite	0	0	7	1	6	11	10	5	15	0	0

1. McIlroy's Port composite flow. a: picrite-basalt; b: olivine-basalt.
2. Cranny Water composite flow. a: picrite-basalt; b: olivine-basalt.
3. Lurigethan composite flow. a: picrite-basalt; b: olivine-basalt.
4. Skerrywhirry composite flow. a: picrite-basalt; b: olivine-basalt.
5. Composite flow below McIlroy's Port flow. Picrite-basalt.
6. Corkey dolerite intrusion. a: olivine-rich facies near margin of dolerite; b: relatively olivine-poor facies in centre of the intrusion.

The modes were determined by integrating stage, each on two or more thin sections of the rock and are expressed in volume percentages. Note: 1a, 2a and 2b have been analysed chemically, Table I.

[1] Includes a little pigeonite.

(c) Cranny Water Composite Flow

This flow, exposed on either side of Cranny Water, two miles west of Carnlough, is at least 100 feet thick, and being practically at the base of the Upper Basalts it forms a prominent rocky scarp overlooking the marked bench due to erosion of the laterites of the interbasaltic zone. The flow is of picrite-basalt with up to 50% of olivine passing upwards into a rock rather less rich in olivine. Near the base of the flow the picrite-basalt contains a layer six to ten feet thick of basalt free from olivine phenocrysts. This layer has a known lateral extent of half a mile. The basalt layer is similar in texture and composition to the groundmass of the picrite-basalt.

The basalt layer presents against the picrite-basalt a sharp upper contact and a lower contact which is gradational over one inch. Both contacts are unchilled and the two rocks are firmly welded together and show no differences in jointing or weathering. The contacts have to be searched for carefully in the field, and are not visible from a distance of more than two or three feet.

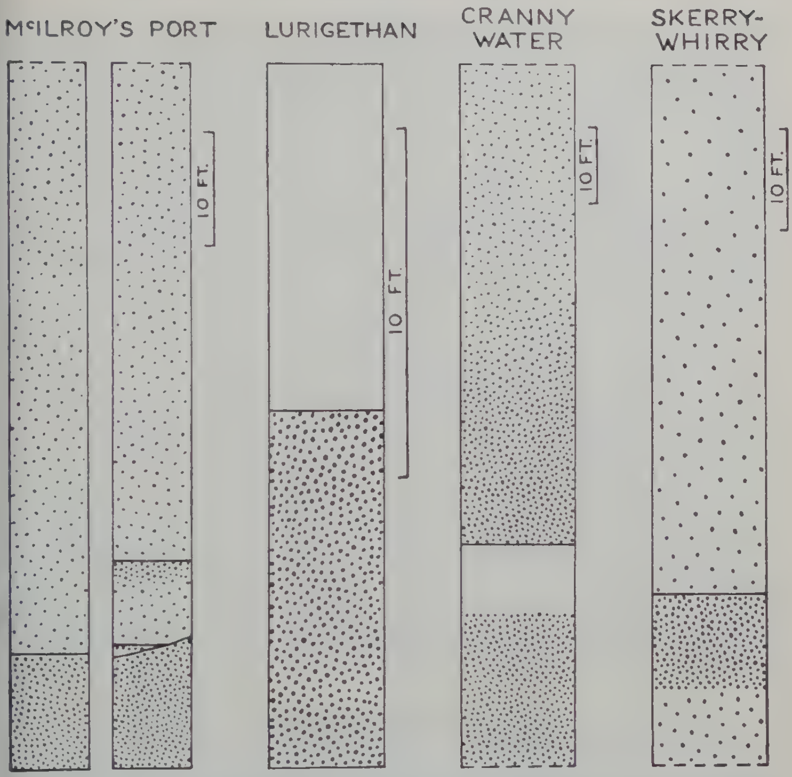


Fig. 6. Comparative vertical sections of four composite lava flows. Density of stippling indicates the relative abundance of olivine phenocrysts

Chemical and modal analyses of the two components of this flow are presented in Table I, 4 and 5, and Table II, 2a and 2b. The picrite-basalt is more than twice as rich in olivine as the olivine-basalt, and this is reflected chemically in its much higher content of magnesia and lower content of silica and alkalies. The high water content of the picrite-basalt is due to a considerable content of zeolites in the groundmass of the rock.

(d) The Skerrywhirry Composite Flow

The fourth example of a composite flow is perhaps afforded by the mass of basalt forming the prominent rocky escarpment of Skerrywhirry, at the base of the Upper Basalts several miles west of Larne. The rock is a coarse-grained olivine-basalt bearing sparse large olivine phenocrysts which increase slightly in amount downwards. Within the olivine-basalt near its base is a layer nine feet thick of picrite-basalt rich in large olivine phenocrysts averaging four millimetres in diameter. There is no apparent variation in composition through this olivine-rich layer, which presents a sharp upper contact against the olivine-basalt and has a lower contact that is gradational over four inches. There is no sign of chilling, and the two rocks are firmly welded together, with no differences in jointing.

A second exposure of this flow has been found in a small rocky scarp two miles south of the main exposure, and here the olivine layer, which shows identical relations towards the olivine-basalt, has a thickness of eight feet.

It does not seem possible to establish beyond doubt that the Skerrywhirry mass is a lava flow. Although the rock is unusually coarse-grained for a lava, three miles to the east, in a road-side quarry at the base of the Upper Basalts on the east of Shane's Hill is an olivine-basalt with large olivine phenocrysts which is identical to the olivine-basalt of Skerrywhirry and, indeed, it could be a continuation of the same flow. There is no doubt that the basalt in this quarry is a surface flow, for it has a weathered amygdaloidal top and its mass is penetrated by long pipe-amygdales.

The olivine layer in the Skerrywhirry mass reminds one of the Palisades sill, where a closely comparable olivine layer has been ascribed to gravity-settling of olivine crystals in place (Walker, 1940), but the sharpness of the upper margin of the picrite-basalt at Skerrywhirry renders this explanation unlikely.

(e) Other Composite Flows

At several places around the sea coast of Islandmagee lavas are exposed with a picrite-basalt lower part and an olivine-basalt upper part. In some this may be due to gravity-settling of olivine crystals (Tomkeieff, 1934) in place, but in others the contact between the two rocks is sharp, although firmly welded and unchilled. A readily accessible example is seen in McIlroy's Port just below the main composite flow there. In this case the picrite-basalt bears some 35% of olivine, the olivine-basalt about 15%, and the contact is quite irregular.

(f) Discussion

The composite flows described above all contain two very similar rock-types, but as may be seen from the comparative sections of Fig. 6 they differ in the arrangement of these rock-types. In all, however, the contacts are typically sharp or gradational over a very short distance, and they are unchilled and the two rocks are firmly welded together. The rock-layers are planar in form, and without intervening slag.

It is clear that gravity-settling of olivine crystals in place is quite incapable of accounting for all these characteristics and one has to postulate that in each case the two contrasting rock-types reached their present position as two separate lava types. These may have arisen by differentiation from a common parent, probably by simple gravity-sinking of olivine phenocrysts, but such differentiation must have been essentially complete before the lavas reached their present position; that is, before movement of the lava had ceased. It does not seem possible to decide whether this differentiation took place before the magma reached the surface or afterwards, but the former is possible, and it may be significant that several of the dolerite plugs in Antrim have an olivine-rich facies near the margin probably due to differentiation during the uprise of the magma in the conduit.

4. DYKES

Associated with the lavas is a swarm of dykes with predominant NNW. or NW. trend, the swarm being most intense in the vicinity of Belfast. The accompanying map, Fig. 1, indicates the distribution of the dykes. The intensity of the swarm ranges from one to thirty or forty dykes per mile, representing a crustal stretch of up to 6%, and the inset to Fig. 1 gives an indication of the distribution of intensity of the swarm expressed as percentage stretch. The intensity probably falls off upwards in the lavas, but exposures are not sufficiently good to enable this to be established.

There are a few dykes which trend approximately at right angles to the swarm, and the following data may indicate that they form a distinct and separate earlier sub-swarm:

A. The dyke feeding a lava flow very low in the lava series on the eastern shore of Brown's Bay, Islandmagee, trends a little S. of W.

B. In Triassic rocks on the shore near Greenisland, seven miles north of Belfast, an ENE. dyke is cut by one trending NNW.

C. In a Chalk quarry at Bellevue, Belfast, a NE. dyke is cut by one trending NW.

D. A NE.-trending dyke one-quarter mile NE. of the White Mountain in the south of Antrim and near the base of the lava succession contains amygdales up to six inches in diameter. These amygdales, larger than any seen in other dykes in Antrim, may indicate the close proximity of the land surface at the time of intrusion of the dyke. The other dykes in the area trend NW. and have small amygdales, being probably intruded when the land surface had been built to a higher level.

The radiating arrangement of dykes around a focus in mid-Antrim suggested by Charlesworth & Hartley (1935) has not been established.

The great majority of the dykes are normal olivine-dolerites of very uniform composition, with basaltic chilled edges. Many have layers of zeolite-filled amygdales parallel to their margins, and often the rock is crinanitic and has zeolites in the groundmass. Prismatic jointing normal to the margins is commonly seen, and one of two types of platy jointing, either parallel to the margins or normal to them and steeply inclined. The attitude of the last is perhaps related to the direction of flow of magma in the dyke-fissure.

Measurement of ninety dykes gives nine feet as the average thickness. Individual dykes can seldom be traced far, largely due to inadequate exposures, but one, the Waterfoot dyke, can be traced for four miles, and other dykes have been traced for distances of up to two miles.

An echelon arrangement is often seen. Where dykes cut the Chalk or Triassic marls they are often extremely irregular in form, with numerous offshoots and protuberances and often a pronounced echelon arrangement. The extreme of irregularity is illustrated by a dyke exposed above the old chalk quarry a short distance north-east of the lower entrance to Glenariff Glen tourist path. Where it cuts basalt lavas this dyke is very regular, but in the Chalk it splits into dozens of sub-parallel veinlets an inch or two thick.

The metamorphism produced by dykes is normally small. The Chalk is recrystallised to a fine-grained, saccharoidal marble to a few inches and rarely to a few feet from the contact; red Triassic marls and sandstones may be decolorised, with local development of poikilitic calcite crystals in sandstones; and basalt lavas are occasionally reddened. Exceptional is the large-scale zeolitisation of lavas and the development of andradite, apatite, magnetite and other minerals in the lavas and underlying sedimentary rocks by dykes at Portmuck, Islandmagee (Walker, 1948), and the pronounced metamorphism of Triassic sandstones (Reynolds, 1940), Old Red Sandstone and basalt lavas by the Waterfoot dyke.

Dykes and Fissure-Eruption

On the western shore of Brown's Bay, Islandmagee, is a particularly convincing example of a lava flow in visible connection with its dyke-feeder. The lava flow in question is in the Lower Basalts about fifty feet above the underlying Chalk, and can readily be located with reference to its position some twenty yards north of the Rocking Stone, a large glacial erratic which forms an unusually convenient landmark.

The flow is of very limited lateral extent, and attains a maximum thickness of ten feet (Fig. 7). It is continuous with a fifteen-inch dyke that cuts vertically through the lower flows and trends a few degrees south of west. The extrusive nature of the lava is clearly indicated by the presence of a red weathered amygdaloidal top, by the absence of cross-cutting relationships and offshoots from the top, and by the local development of pipe-amygdales along the base.

The dyke-feeder is exposed through only a small vertical height, but appears to increase somewhat in thickness downwards. That it constitutes a true dyke and not a fissure in the underlying flow filled from above is indicated by the two wedge-shaped offshoots into the top of the underlying flow. This evidence is significant in view of the fact that such cracks filled from above are common in the lavas of Antrim; the writer considers it very probable that the locality claimed by Patterson (1950) as an example of fissure-eruption is such an instance of infilling from above of cracks in the bulbous front of pahoehoe flow-units.

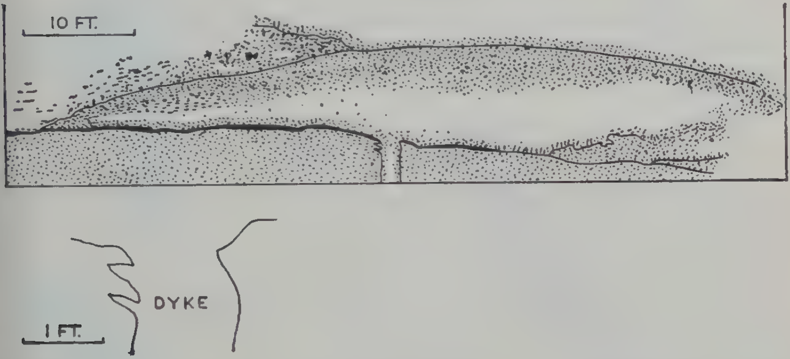


Fig. 7. Section of fissure-erupted lava flow, Brown's Bay, Islandmagee. Stippling indicates amygdales. Below: detail of join of dyke and lava

Petrographically the lava is a normal, medium-grained olivine-basalt consisting of small olivine replaced by iddingsite, normally zoned labradorite, ophitic titanaugite and accessory magnetite together with an abundance of secondary minerals in amygdales and replacing the primary constituents of the rock. The dyke is of similar composition but rather finer in grain, with a little glass at the contact. Both dyke and lava contain numerous zeolite-bearing amygdales up to half an inch in diameter.

The great scarcity of known examples of lavas in visible connection with their dyke-feeder in the Thulean Province has often aroused comment (Tyrrell, 1937). The writer's experience in the post-glacial lava fields of Iceland suggests that when a fissure-eruption takes place lava and dyke-feeder often may not remain in continuity, but may be separated by the scoriaceous basalt of the spatter rampart, spatter craters or cinder cones that are usually built along the line of the fissure.

About 300 yards north of Black Head on the coast of Islandmagee there is a section in the raised beach cliffs of what appears to have been a cinder cone at least twenty feet high resting upon a flat platform of lavas. The cone is a confused jumble of irregular pieces of basalt, mostly amygdaloidal, ranging in size from a few inches to over one foot. A crude stratification parallel to the sides of the cone is marked by layers of blocks of different size.

On the southern slope of the cone is a group of very thin lavas in which the sharp bending-over of the basal pipe-amygdales attests to the movement of the lava down the side of the cone. Lavas and cone are cut by a cluster of dykes, and one of the thin flows resting on the cone on its south side may possibly be continuous with one of the dykes, although this is not certain. Although proof that this locality is the seat of fissure-eruption is lacking, it is clear from observations in Iceland that in searching for signs of fissure-eruption in older basaltic terranes the type of evidence found at Black Head is perhaps more to be expected than visible continuity of dyke and flow.

5. DOLERITE PLUGS

Some thirty Tertiary dolerite plugs are now known associated with the Antrim Basalts, this figure including the six new ones found by the writer during the past few years. The known plugs are distributed over the 800 square miles of plateau-basalts that are reasonably well exposed, to give an average density of one plug per thirty square miles. It can be seen from the map, Fig. 1, that most lie in the eastern half of the basalts, and the density there is nearer one plug per twenty square miles.

The following are the newly discovered plugs:

A. Corkey, a plug of olivine-dolerite with olivine-rich facies near the margin, passing upwards into a sill in basalt lavas. The intrusion forms the hill (including Craigacullin) NE. of Corkey, nine miles E. of Ballymoney in NE. Antrim.

B. Glasmullen, a small plug of olivine-free dolerite in basalt lavas, on the plateau SE. of Crockalough, two miles SSW. of Lurigethan summit.

C. Doonbought, discovered independently by E. M. Patterson (personal communication) and the writer, a small plug of ophitic olivine-dolerite in basalt lavas, six miles north of Ballymena.

D. Trosk, an elongated plug of picrite-dolerite in Upper Basalts, one-quarter mile north of Loughnatrosk and two miles NNW. of Carnlough village, E. Antrim.

E. Ticloy, an elongated plug of olivine-dolerite in basalt lavas, crossing the stream, Ticloy Water, three-quarters of a mile E. of Ticloy Hill, and four miles SW. of Carnlough.

F. Parkgate, an elongated plug of olivine-dolerite in basalt lavas on the eastern side of Donegore Hill with a second small plug to the north, two and a half miles NNW. of Templepatrick.

The comparative plans of Fig. 8 give an indication of the range of size and shape of these intrusions. It can be seen that the average diameter is of the order of 200 to 300 yards and that most are elongated NW. or NNW.

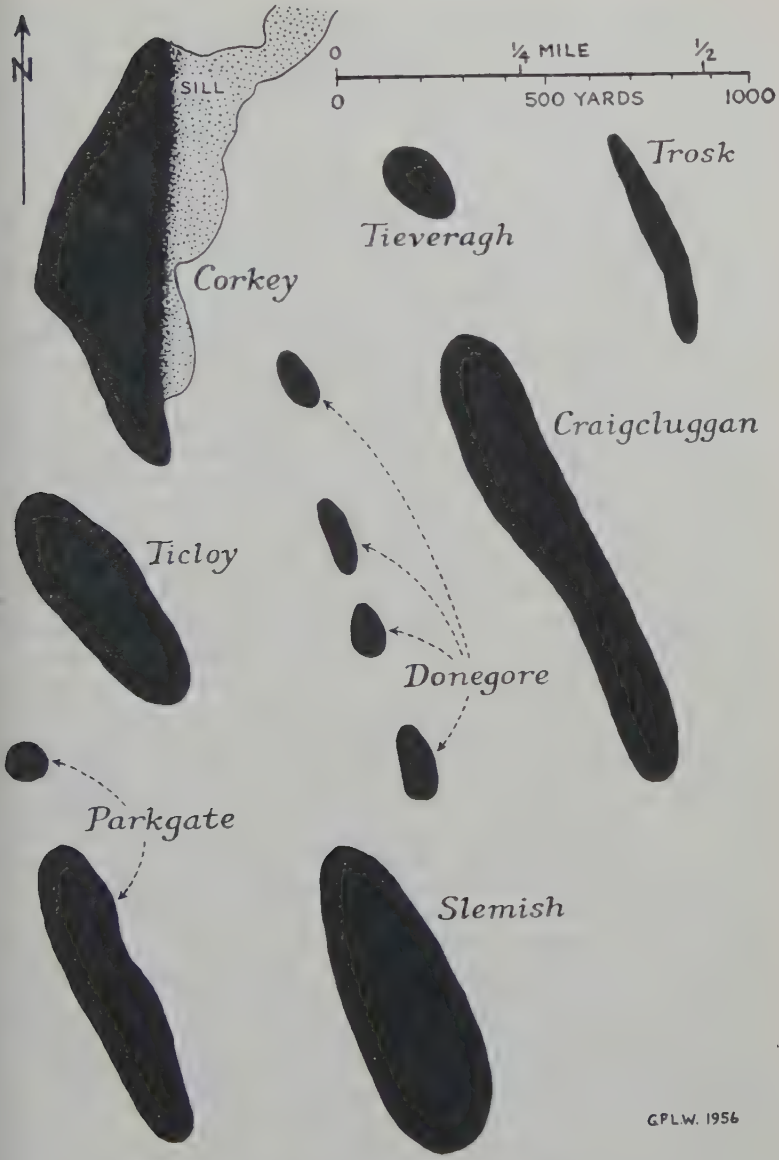


Fig. 8. Comparative plans of dolerite plugs in Antrim

and parallel to the regional dyke swarm. Contacts, where seen, are usually steeply inclined or vertical, but in general the contacts are not well exposed for the dolerite of the plugs projects as rocky knolls above the surrounding country, and the contact is usually obscured by scree or drift. The Slemish plug forms a particularly striking prominence rising steeply some 500 feet above the basalt country.

The metamorphism produced by the plugs varies greatly, from an almost insignificant amount, not more than that produced by the average dyke, to a considerable amount as at Scawt Hill (Tilley & Harwood, 1931), Ballycraigy Bridge, Tievebulliagh (Tomkeieff, 1940a; Agrell & Langley, 1958) and Tieveragh (Tomkeieff, 1940a). The intensity is probably related to the length of time magma flowed through the pipe. The Waterfoot dyke, and intrusions at Portmuck, Islandmagee, are the only dykes known to produce comparably intense metamorphism.

Some of the plugs have a radial-columnar jointing while others have a rather platy vertical jointing more or less parallel to the elongation. With three exceptions all are normal ophitic olivine-dolerites or crinanites of very uniform composition, averaging 15 to 25% of olivine. The exceptions are the intrusions of Carnmoney and Glasmullen, which are of tholeiitic rock free from olivine, and that of Trosk, which is of picrite-dolerite. Several of the plugs of olivine-dolerite (Tievebulliagh, Tieveragh and Corkey) have a marked concentration of olivine near the margin, giving rise to picrite-dolerites with 30 to 60% of olivine (Table II, 6a and 6b).

(a) Sills

Sills are extremely rare in the Antrim Basalts, and apart from occasional small offshoots from dykes only two are known, namely Knocksoghey (Tomkeieff & Patterson, 1947) and the newly discovered sill of Corkey. In contrast, a number of dolerite sills are known in the sub-basaltic sedimentary rocks outcropping around the periphery of the basaltic plateau. All are normal olivine-dolerites or crinanites similar in composition to the dykes and plugs. Veins and sheets of dolerite-pegmatite are abundant in some of the sills, notably in that of Fair Head.

The scarcity of sills in the lavas is probably real rather than apparent, for sills in lavas are usually quite readily recognised despite the similarity of the rock-types involved. This scarcity must be bound up with the relatively poor stratification of the lavas and the difficulty experienced by intrusive magma of forcing its way laterally along the flow boundaries.

(b) Vents

In no case is it possible to demonstrate continuity between plug and lava flow, although the intense metamorphism around some plugs must indicate copious eruptions of basaltic magma from them. Direct evidence that some of the plugs communicated with the surface in Tertiary times is found in the association of some with agglomerate.

The best-known agglomerate-filled vent is that of Carrickarade on the north coast of Antrim (Symes, Egan & McHenry, 1888; Tomkeieff & Patterson, 1948), with bedded ash in the lava succession near by. Rohleder (1925), Dawson (1951) and Patterson (1955a) have interpreted as agglomerate-filled vents a number of occurrences of basalt breccia in the north of Antrim, and the present writer knows of similar occurrences along the coast north-west of Larne. It seems more likely, however, that these breccias are due to collapse of basalt into solution pipes in the Chalk (Charlesworth, 1935) or are rootless vents and are not related to the conduits that brought the lava to the surface.

Along the western edge of the dolerite mass of Ballygalley Head is a belt some fifty to a hundred yards wide of agglomerate containing fragments of Chalk, Trias and basalt. This agglomerate, not hitherto described, is closely similar in character to some of the agglomerate near Carrickarade on the north coast of Antrim. Two miles west of Ballygalley Head, very low down in the lava succession on the escarpment of Knock Dhu, there is a bed at least twenty feet thick, for the most part obscured by scree, of chalky agglomerate of identical characters to that associated with the dolerite. There is no proof that the two are related, but it seems very likely that they are, and that the bedded agglomerate of Knock Dhu was erupted from the Ballygalley Head vent.

The attitude of platy jointing parallel to the margin and columnar jointing normal to it suggests that the dolerite mass of Ballygalley Head may not be a vertical plug with cylindrical shape, as proposed by Tomkeieff (1935) but rather funnel-like or cup-like in form, and perhaps even a crater-filling.

(c) Re-interpretation of the Donegore Dyke

The Donegore dyke, some miles north-west of Belfast, was first studied by Hull, Duffin & Du Noyer (1876) of the Geological Survey of Ireland. It was later remapped by Cole (1912, 93) who described the intrusion as a NNW.-trending dyke. A critical re-examination of the exposures appears to necessitate modification of this interpretation of the form of the dolerite.

Exposures of the Donegore dyke are confined to four rocky knolls aligned NNW. along a distance of two-thirds of a mile. The writer believes that these represent four separate dolerite plugs (Fig. 8). Proof, in the exposure of basalt lavas between the knolls, is absent, but in two of the knolls in which the dolerite is banded the banding is concentric with the edge of the knoll and inclined inwards in funnel-like fashion. This is strongly suggestive of each knoll being a separate entity. The banding is best seen in the southernmost knoll, The Craig. The bands, an inch or two

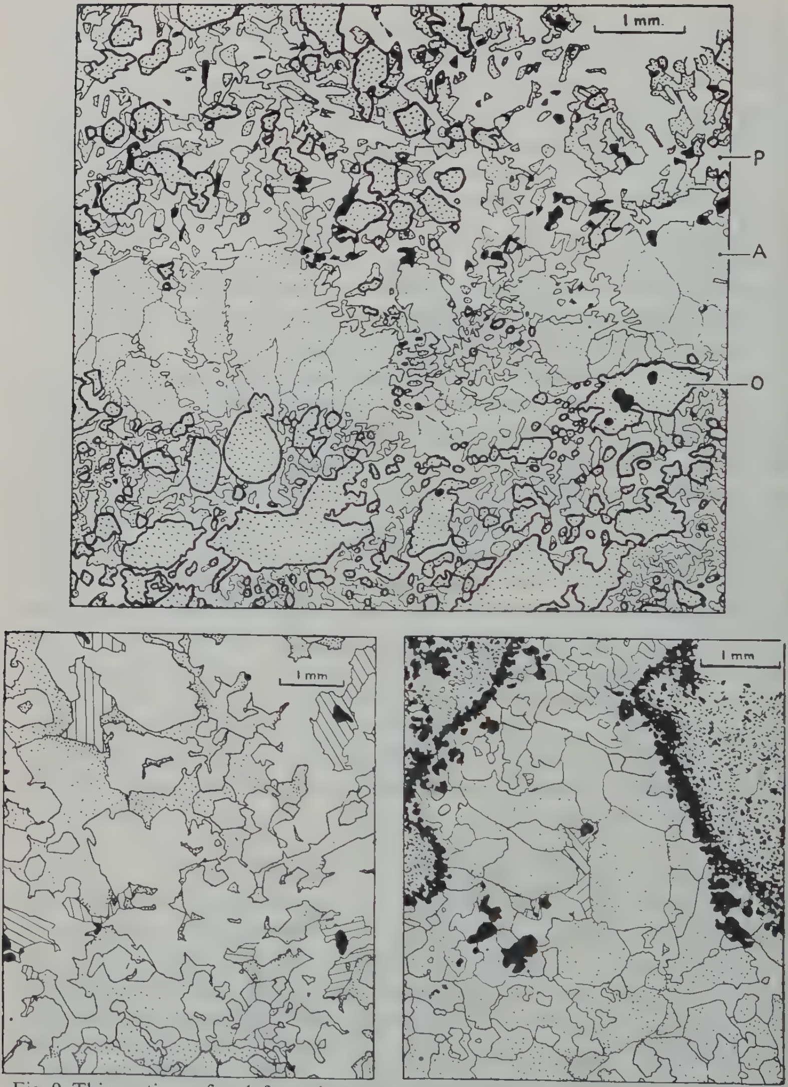


Fig. 9. Thin sections of rock from the McIlroy's Port composite lava flow, Islandmagee

Above: Contact between two components, shore just south of vent. Olivine-basalt above, picrite-basalt below, with layer of augite along contact. O = olivine, A = augite, P = plagioclase

Below, left: Sodalite-rich pegmatite. Sodalite, blank; aegirine-augite, stippled (the density of the stippling indicating the depth of colour in zoned crystals); plagioclase, lined

Below, right: Pegmatite rich in pyroxene in contact with altered basalt on either side. The basalt is a fine-grained aggregate of aegirine-augite and sodalite, liberally dusted with magnetite, with a marked concentration of magnetite at the contact thick, are marked by the presence or absence of tiny amygdales or ocelli, and the dip ranges from 10–30° near the edge of the knoll to 30–70° near the middle.

(d) Origin of the Plugs

It requires a considerable effort for basaltic magma to manage to spurt up to the surface along a narrow fissure from a region near the base of the crust. In all probability the magma of a dyke in many cases never succeeds in attaining the surface at all, or reaches it with so little energy left that only an insignificant eruption occurs.

Iceland is perhaps the place where present-day conditions of eruption most closely resemble those which obtained in Antrim in Tertiary times. The fissures (gjás), which are one of the spectacular features of the newer volcanic belt of Iceland, form gaping cracks, often individually some miles long, which cross the country in a curving swarm from the north coast to the south-west peninsula, and are almost certainly the surface manifestation of such dykes which have failed to reach the surface. In Iceland voluminous outpourings of lava have, however, taken place from some fissures, and likewise it is clear that some of the dykes in Antrim must have been the seat of fissure-eruption.

In a typical fissure-eruption outpourings of lava in at least some stages of the eruption is confined to short lengths of the fissure, due to the contest between rate of loss of heat and rate of accession of magma. Igneous erosion in a vigorous eruption, perhaps aided by explosion, will tend to enlarge the fissure along such lengths, and if successful will swing the delicate thermal balance strongly in favour of the magma, and the ultimate result may be the formation of elongated plug-like conduits of Antrim type along the original dyke.

In no case in Antrim has connection between plug and the inferred original dyke been demonstrated, but both the Tieveragh and Trosk plugs are in line with the Waterfoot dyke, exposures of which bridge half the distance between the two plugs. Straidkilley and Scawt Hill plugs are approximately on the same line, Tievebulliagh, Glassmullen and Craigcluggan lie on a parallel line three miles to the west, both of these lines being parallel to the dykes in the area. These alignments are, if nothing else, very suggestive.

The Donegore dyke, Fig. 8, if one accepts the interpretation of the field relations put forward in this paper, can perhaps be regarded as an early stage in the development of an elongated plug; the four separate plugs have not coalesced. The Parkgate plug, with its solitary satellite plug to the north, is an intermediate stage, and the Craigcluggan plug may be regarded as representative of the final stage in the evolution of an elongated plug of Antrim type from a dyke.

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Field Meeting at Wrotham and the Maidstone By-Pass

Saturday, 25 April 1959

Report by the Director: R. CASEY

Received 28 April 1959

THE PURPOSE of this meeting was to examine new sections in the Lower Greensand and Gault made available by the construction of a by-pass road at Maidstone. A halt was first made at Wrotham in order to visit the Rugby Portland Cement Company's workings at Ford Place, situated immediately north of the pit described by E. E. S. Brown (1941, 5, 8). These workings cut through the top of the Lower Greensand (Folkestone Beds) and most of the Gault and provide a standard of comparison for the scattered exposures of the by-pass.

At Ford Place the buff, incoherent sands of the Folkestone Beds display high-angle current-bedding and are succeeded abruptly by glauconitic clayey sands and sandy clays which form a passage into the blue-grey clays of the Gault. These passage beds are about eight feet thick and contain in their upper part numerous gritty phosphatic nodules concentrated in three main seams, the whole referable to the *mammillatum* Zone. Differential oxidation of the glauconite causes a gradual colour-change upwards from rusty brown to dark green. Fossils are not common in the topmost seam of nodules, though collecting over the years has brought to light an interesting set of ammonites comparable with those found in the matrix of the Main *mammillatum* Bed and in the Sulphur Band at Folkestone, but best known from their occurrence at Machéroménil (Ardennes), France. The finds include *Protohoplites* (*Protohoplites*) *archiacianus* (d'Orbigny), *P.* (*P.*) *michelinianus* (d'Orb.), *P.* (*P.*) *latisulcatus* (Sinzow), *P.* (*Hemisonneratia*) *puzosianus* (d'Orb.), *P.* (*H.*) *gallicus* (Breistroffer), *Otohoplites guersanti* (d'Orb.), *O. auritiformis* (Spath), *Pseudosonneratia* spp. nov., *Sonneratia dutempleana* (d'Orb.), *Tetrahoplites* cf. *subquadratus* (Sinzow) and *Tegoceras gladiator* (Bayle). From the nodule-bed in the overlying *dentatus* Zone, which floors part of the workings, the party obtained prodigious quantities of *Hoplites*. An intensive search of this bed (for which Mr. R. A. Milbourne and colleagues were chiefly responsible) had in the past produced ammonites identifiable as *Oxytropidoceras roissyanum* (d'Orb.), *O. mirapelianum* (d'Orb.), *O.* sp. nov. cf. *cantianum* Spath, *Mojsisovicsia delaruei* (d'Orb.), *Falloticeras* cf. *proteus* (d'Orb.), together with species of *Metahamites* and Brancoceratidae. The fauna has much in common with that of the *dentatus* Zone of Escragnolles, in the Alpes Maritimes Department of France, to which area the genus *Falloticeras* was hitherto believed to be endemic. In its essential features the rest of the Lower Gault is like that of Dunton Green (Wright, 1947) and Greatness Lane, Sevenoaks (Milbourne, 1956), differing from the Folkestone sequence in its expanded development of the upper part of the *dentatus* Zone and its reduced thickness of *lautus* Zone.

Examination of the by-pass excavations commenced at the 'clover leaf' north of the Chiltern Hundreds Inn, on the Detling road, on the north-east side of Maidstone. From here to a point where the by-pass route crosses the Maidstone–Ashford railway at Chrismill Bridge, nearly three miles to the south-east, there are isolated cuttings in the Gault, which, pieced together, give the following succession:

	Zone	Thickness
Upper Gault	*Stoliczkaia dispar*	20 ft. +
	Mortoniceras inflatum	45–50 ft.
Lower Gault	*Euhoplites lautus*	3–4 ft.
	Hoplites dentatus	20 ft.
	Douvilleiceras mammillatum	5 ft.

The Director reminded members that the idea of a large gap in the Lower Gault succession in this area, expressed by some authors, had been refuted by the Geological Survey (1957, 48), and work on the by-pass exposures had confirmed that despite the very thin *lautus* Zone the sequence was complete. On the recently published one-inch geological map of the Maidstone district (Sheet 288) the site of the 'clover leaf' was shown as lying at the eastern end of a long strike fault that affected the junction of the Folkestone Beds and the Gault. The new exposures, not available to the surveyors, had amplified information on this faulted ground. It appears that a subsidiary fault extends eastwards from the southern boundary of Park Wood into Horish Wood, forming the northern limit of a steeply dipping wedge of strata in which the Folkestone Beds–Gault junction is preserved intact. At the western end of Horish Wood, Folkestone Beds are brought against the top of the *inflatum* Zone of the Upper Gault, indicating a minimum throw of seventy feet.

The cutting through Horish Wood is the most important of the new sections. Over one hundred yards long and up to fifteen feet high, it exposed at the bottom a bed of glauconitic marl, about two feet thick, resting on an irregular surface of normal Gault clay. The bed held a great quantity of black and brown phosphatic nodules, many recognisable as rolled internal moulds of ammonites and other fossils, and had yielded water-worn bones and teeth of fish and marine reptiles, neural plates of turtles, bones of pterodactyls, and carapaces of crabs. The bed had no definite top, the nodules and glauconite dying out upwards. In its field relations, lithology, and fossil content the bed is strikingly similar to the well-known Cambridge Greensand, though study of the ammonites, of which more than fifty species have been identified, shows that it does not lie on quite the same horizon. The true Cambridge Greensand forms the base of the Chalk and contains a remanié of strata equivalent to Beds XII and XIII of the Folkestone Gault, whereas the bed exposed in Horish Wood represents in condensed form the forty feet of clay of Beds XI and XII of Folkestone, Bed XIII of the Gault here intervening between the 'Greensand' and the Chalk. It is evident that Bed XII of Folkestone, itself a 'greensand' bed, is a feeble expression of the same phase of interrupted deposition. Some of the more common and interesting fossils found in the 'Greensand' at Horish Wood are listed below, determinations of the reptilia being those of Dr. W. E. Swinton: Reptilia: *Ichthyosaurus campylodon* Carter (vertebrae and ? ribs) *Polyptychodon interruptus* Owen (teeth), *Plesiosaurus cantabrigiensis* (Lyd.) (vertebra), *Ornithocheirus* spp. (wing bones), Pisces: *Ischyodus* sp. (large dental plates), *Lamna* ? (teeth and vertebrae), Lamellibranchiata: *Aucellina gryphaeoides* (J. de C. Sow.), '*Cardita*' *tenuicosta* (J. de C. Sow.), *Diploschiza* sp. (encrusting nodules), Cephalopoda: *Mortoniceras* (*Mortoniceras*) *inflatum* (J. Sow.), *M.* (*M.*) *potterense* Spath, *M.* (*M.*) *fissicostatum* Spath, *Hysteroceras bucklandi* (Spath), *H. carinatum* (Spath), *H. subbinum* Spath, *Prohysteroceras* (*Goodhallites*) *goodhalli* (J. Sow.), *P.* (*Neoharpoceras*) *coptense* Spath, *Cantabrigites cantabrigensis* Spath, *Callihoplites auritus* (J. Sow.), *C. tetragonoides* Spath, *C. seeleyi* Spath, *Epihoplites gibbosus* Spath, *Anahoplites costosus* Spath, *Discohoplites coelonotus* (Seeley), *Euhoplites alphalautus* Spath, Gen. nov. ('*Placenticeras*') sp. nov., *Scaphites simplex* Jukes-Browne, *Stomohamites duplicatus* (Pictet & Campiche), *S. funatus* (Brongniart), *Idiohamites favrinus* (Pictet), Crustacea: *Notopocorystes stokesi* (Mantell), *Homolopsis edwardsi* Bell.

Owing to the cutting having been allowed to weather down during the winter, the party could inspect this remarkable bed *in situ* only at one or two points, though the nearby dumps of excavated material provided good fossil-hunting.

Proceeding to Water Lane, about two miles to the south-east, the party next examined sections of the top of the Lower Gault and the lower part of the Upper Gault extending through Longham Wood.

Tea was taken in Maidstone, where the party, numbering thirty, accorded a vote of thanks to the Director and to Miss E. W. Andrews, who had acted as Secretary for the Meeting. It rained all day.

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Field Meetings along the North Craven Fault

NORTH-EAST LANCASHIRE GROUP

12 July and 23 August 1958

Report by the Director
with
Note on the Malham Tarn Silurian Inlier

by I. A. WILLIAMSON

Received 19 November 1958

THE PURPOSE of the meetings was to study the general geology of the area along the North Craven Fault, between Wharfedale and Ribblesdale, near the south margin of the Askrigg Block. On the first meeting the party travelled from Threshfield near Grassington to Malham, and on the second, continued from Malham to Stainforth, in Ribblesdale. Both meetings were attended by fifteen members.

Saturday, 12 July

During a short halt at Threshfield the Director gave a brief outline of the geological succession to be demonstrated and discussed the nature of the North Craven Fault. This fault, first noted by Phillips (1836), is the northernmost member of the Craven Fault System and extends in an essentially west-north-westerly direction from Pateley Bridge for over thirty-five miles to beyond Ingleton. The nature of the displacement has been variously regarded. Phillips (op. cit., 104) considered it to be a normal fault downthrowing to the south, whilst Marr (1899, 351) suggested it to be a low angle thrust. The most important contribution is that of Wager (1931) who, from a study of the deflection of jointing near the fault plane, considers it to be a tear fault developed during the Hercynian orogeny. This thesis of lateral displacement is considered by Anderson (1951, 90) to be the principal movement to which the vertical movements, resulting in a downthrow to the south, are only subsidiary. In the area visited on the two meetings the fault affects Silurian and Carboniferous strata.

The party walked to the Threshfield Lime Works at Skythorns, where, by courtesy of the Settle Lime Company, they were able to examine the abandoned quarrys on Bell Bank on the north side of the fault. Here about sixty feet of D_1 limestones are exposed and are particularly interesting due to their widespread dolomitisation. In the lowest quarry (980640)[1] dolomitic limestone outcrops throughout. (Dolomitic limestone is here taken as a carbonate rock composed of the mineral Dolomite. The use of the noun limestone is taken to embrace that group of carbonate rocks composed largely of calcium carbonate.) The rock, yellow when fresh, weathers brown and is well bedded. In the upper quarry (980641) the transgressive nature of the dolomitic limestone is apparent, particularly on the north-west face where brownish dolomitic limestone occupies a channel-like hollow in white limestone. The dolomitic limestone is clearly secondary, no doubt the result of metasomatic alteration of limestone adjacent to the North Craven Fault. Throughout the area between Wharfedale and Ribblesdale, the limestone adjacent to the fault shows some dolomitisation. The *Cyrtina septosa* Band is well exposed along the top of the east face of the quarry. This band, first noted by Cosmo Johns (1908, 397), is particularly well developed throughout the area and was used by Garwood & Goodyear (1924) as a marker horizon in mapping the south-western part of the Askrigg Block. Upon leaving the quarry a fine slickensided block of dolomitic limestone was examined opposite the quarry offices (981639) and close to the North Craven Fault.

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[1] All grid references lie in the 100 kilometre square 34 (SD).

The party then proceeded to Wood Nook (973641), from whence the North Craven Fault can be traced in a west-north-westerly direction almost continuously to Ribblesdale. Immediately behind Wood Nook a small quarry exposes a coarse sandstone, one of the lower Namurian (E_1) beds of the Bordley outlier at present being surveyed by the Director. From here the North Craven Fault, throwing Great Scar Limestone on the north against Lower Namurian sandstones and shales on the south, was demonstrated. At Height Laithe (960645) the outcrop of the fault plane is marked by a linear arrangement of pot-holes. Near to here, Height Cave (964646) was seen, but owing to several large bulls in its vicinity could not be visited. When excavated in 1890 the cave contained archaeological remains of considerable importance.

Between Bordley Beck (948648) and Gordale Beck (911655) the North Craven Fault displaces Avonian limestones and, owing to the relative lithological similarity of the rocks, does not result in any marked topographic feature, particularly as much of the ground is obscured by drift. The party followed the prominent dry valley, the northerly continuation of Bordley Beck, to Mastiles Lane and so to Cow Gill. Here (931652), the proximity of the fault is indicated by a large pot-hole and a small outcrop of dolomitic limestone.

Along High Bank (928653) the fault is obscured by thick drift for about half a mile until a linear development of pot-holes and a slight topographic feature along Low Stony Bank (920653) renders it easily traceable to Gordale Beck. Here the fault outcrops, throwing Silurian sandstones on the north against Carboniferous D_1 limestones on the south. In the immediate vicinity the position of the fault may be easily placed by a marked vegetation change.

After having lunch an examination was made of the middle D_1 limestones on the south of the fault. These outcrop on both sides of the stream in the vicinity of several prominent small limestone stacks where the *Cyrtina septosa* Band occurs. At this point there was some discussion concerning the origin of the deep gorge of Gordale. The valley, dissecting the 1300 foot erosion stage of Sweeting (1950), shows the first rejuvenation stage of that author. The Director expressed the view that the relatively small volume of water flowing in the valley was formerly augmented by drainage from Malham Tarn along the foot of Great Close Scar (900665), prior to the formation of the present outlet.

The North Craven Fault was then demonstrated where the dip of the limestone can be seen to increase considerably near the actual outcrop of the fault. At this locality also, the limestone was brecciated and dolomitised. On the north of the fault the Gordale Silurian outcrop (described in the note appendixed to this report) was examined before the party continued along Mastiles Lane to Water Sinks Gate.

The line of the fault was seen to be marked by a topographic feature and a linear arrangement of pot-holes on the north of Torlery Edge (899654). From here also the position of the fault could be traced to beyond the Smelt Mill chimney (883660). The fault was crossed just below Water Sinks Gate where the overflow from Malham Tarn 'sinks' into the limestone amidst a ruckle of boulders. It was noticed that, despite the heavy rainfall of the previous days, the underground drainage took place a considerable distance above the former sink-hole.

The dry valley below here was then followed, the party passing the shaft sunk by the Craven Pot-hole Club a few years ago. This was an attempt to reach a possible cavern behind Malham Cove. After sinking through eighty feet of limestone the shaft was abandoned. Much interest developed around a particularly fine example of a stylolite seam in a large block of limestone amidst the debris excavated during the construction of the shaft. Stylolites are particularly common in the Great Scar Limestone though they are often missed by the casual observer.

Where the valley became constricted (892650), '*Cyrtina*' *septosa* limestones were again seen as two bands separated by about thirty feet of mainly detrital limestone. Below here is the celebrated dry valley of the Watlowes at the rear of Malham Cove. The valley, flanked on the east by Combe Scar, shows the step-like topography so characteristic of many valleys eroded in the Great Scar Limestone, a topography which is due to the occurrence of master bedding planes limiting lithological cycles in the limestone. Schwarzacher (1958) has shown that it is possible to correlate the individual beds in the limestone by the use of these lithological cycles alone.

At the top of Malham Cove the party crossed the magnificent limestone pavement before descending to the base, where the River Aire rises. In 1953 frogmen attempted to penetrate this spring, but after seventy feet the passage becomes too constricted to permit further exploration.

After tea in Malham village the party returned to East Lancashire.

Saturday, 23 August

Commencing at Malham the Cove road was ascended from which excellent views were had of Malham Cove and the district to the south of the Mid Craven Fault. At Robin Hill Rigg (891644) the '*Cyrtina*' *septosa* Band was seen at the roadside, to the east of which the band is displaced by the north-westerly trending Langscar fault. At Langscar, an excellent exposure of the band was examined in the escarpment by the wallside (88456537). At this locality the limestone below the band is current bedded.

From here Haw Knabs was ascended, close to the summit of which (872656) the chert beds above the Bryozoa Series of D_2 age yielded numerous and well-preserved fossils. The western face of Haw Knabs is a fault escarpment developed along a north-westerly trending fault marked by numerous pot-holes. A north-easterly trending fault separates the limestones of Haw Knabs from the Black Hill Grit composed of a coarse pebbly sandstone overlain by a finer, more flaggy sandstone. The Black Hill Grit is correlated by Versey (in Hudson, 1930, 320), on the basis of the heavy mineral assemblage, with the Grassington Grit of late E_2 age. The northern slope of the hill is crossed by the North Craven Fault (865664), immediately to the south of which a dark, shelly Yoredale limestone of lower D_2 age is seen to underlay the sandstone. The chief interest of Black Hill is this evidence for a diastem during P_2 and early E_1 times in this area, a suggestion recently made by Rowell & Scanlon (1957).

From the summit of the hill, the line of the North Craven Fault to the east was seen to be marked by a slight vegetation change as far as the Smelt Mill chimney. To the north of the fault the low, drift-covered ground of the Malham Tarn Silurian inlier contrasts strongly with the surrounding limestone fells. The North Craven Fault to the east of the hill is obscured by superficial deposits though its position is indicated by several sections in Cowside Beck.

After lunch the Silurian outcrop near Capon Hall was examined before the party walked through a high level overflow channel north of Black Hill. This hitherto undescribed channel (865665) breaches the Aire–Ribblesdale watershed at 1400 feet O.D., and slopes to the east. It is therefore suggested that it was formed by easterly drainage from a proglacial lake to the west of Black Hill.

In the headwaters of Cowside Beck (857663) a fault throwing Yoredale shales yielding *Posidonia* sp. against well-bedded limestones to the south was seen. A partly dolomitised fault breccia marks the fault line. Below here, in Cowside Beck, Yoredale shales outcrop until the stream crosses the North Craven Fault (855666), where fine grey Silurian sandstones of the Ribblesdale inlier outcrop. The Silurian on the north side of the fault was seen in a series of well-exposed sections to just above Henside Lane where the stream exposes a magnificent section of the North Craven Fault (84756680). Here, Silurian sandstones are faulted against Yoredale limestones. A dolomitised fault breccia, trending north-west and inclined steeply to the south, can be followed for twenty yards as a dyke-like rib (Kendall, 1912, 130).

The stream sections below this outcrop are masked with drift and alluvium. Accordingly the party left the stream and ascended Langcliffe road obtaining excellent views of the Ribblesdale Lower Palaeozoic inlier and the Craven uplands.

Winskill Stones (836666) were next visited where some striking Silurian sandstone erratics are supported on plinths of Carboniferous limestone. The party then returned to Cowside Beck at Catrigg Force (832671). Here a series of waterfalls are situated close to a branch of the North Craven Fault. In the stream below the falls a bed of dolomitic limestone and several outcrops of fault breccia were observed. The lower reaches of Cowside Beck, also termed Stainforth Beck, recross the line of the North Craven Fault and again expose Silurian rocks. Several good sections were examined in the Austwick Flags and Grits which, in one locality (825676), showed evidence of contemporaneous slumping. Immediately upstream from here some fine sections in till are exposed on the northern bank.

Around Stainforth much drift obscures the solid geology until the River Ribble is reached at Stainforth Bridge, south of the North Craven Fault. At Stainforth Force light grey limestones of the *Michelinia grandis* Zone (C_2) were examined. In the area this forms the lowest bed present in the Carboniferous succession. Above the bridge the fault crosses the river though its exact outcrop cannot be traced until west of Banks Barn (812679) where it forms a prominent feature along the north face of Smearsett Scar.

At Stainforth the meeting was concluded. A vote of thanks was proposed to the Director by the chairman of the group, Mr. J. Ranson.

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Note on the Malham Tarn Silurian Inlier

by I. A. WILLIAMSON

THE EXISTENCE of this inlier, situated amidst the Lower Carboniferous, was first recorded by Dalton (1872, 17) during the course of the geological survey of that area. It is also interesting to note that Davis (1878) recorded a very small Silurian inlier at the foot of Gordale (about 914640), though this section is now obscured. The Malham Tarn inlier, limited to the south by the North Craven Fault, is separated from the larger Lower Palaeozoic inlier of Ribblesdale by less than half a mile of lower Carboniferous Limestone. It is but poorly exposed, with outcrops confined to the extreme south-east and south-west at Gordale (911656) and Capon Hall (866665) respectively.

The Gordale outcrop consists predominantly of hard, blue-black siltstones, containing locally abundant small irregular patches of iron pyrites. Several thin shale beds also occur. In a small stream, north of Mastiles lane (912656), the siltstones contain very rare and poorly preserved *Monograptus* sp. The well-cleaved nature of the beds renders fossil discovery particularly difficult.

Between Gordale and Capon Hall the inlier is obscured by superficial deposits and therefore the northern margin can only be inferred. South of Capon Hall several unfossiliferous outcrops of fine grey sandstone constitute the westward limit of the inlier. One or more finely cleaved green shale bands occur here also, since fragments of this rock are fairly abundant in some of the fields when ploughed. From comparison with the Ribblesdale inlier the Malham Silurian rocks may be correlated with the Austwick Grits and Flags of Wenlock age.

The structure of the inlier is clearly a continuation of that of the Lower Palaeozoics of Ribblesdale where the rocks are folded in a broad synclinorium trending east–west and pitching to the east. At Malham the beds are well cleaved, and a study of the relationship of the cleavage with the bedding shows the Malham outcrops to be situated on the southern limb of an anticline trending east-south-east. In Gordale, just below the fossil locality mentioned, an outcrop of crushed rock is probably situated along a fault.

The actual basal-Carboniferous unconformity above the inlier cannot be seen, though its position may be proved to within one yard in Gordale. Here also (911658), about twenty feet above the unconformity, a grey crinoidal limestone contains small phenoclasts of sandstone, presumably derived from the underlying Silurian. At Capon Hall, a limestone conglomerate containing abundant Silurian pebbles and a sandy conglomeratic limestone, were recorded by Dalton (op. cit., p. 18). Unfortunately this exposure is now obscured though there is an outcrop of sandy limestone near the position of the unconformity.

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WRITTEN CONTRIBUTIONS TO THE DISCUSSION OF A PAPER PREVIOUSLY TAKEN AS READ

The Editor

Dear Sir,

The publication (*Proc. Geol. Ass., Lond.*, **69,** 205) of L. Knowles' & F. A. Middlemiss' work on 'The Lower Greensand in the Hindhead Area of Surrey and Hampshire' is of great interest. May I comment on a few points raised, within the area covered by the Ordnance Survey Surrey Sheet No. 37 SE., which I mapped some years ago?

How much reliance can be placed on dips as measured in the field? False-bedding, in the relatively few good exposures that do occur, in the Hythe Beds and the Bargate Beds can give a very misleading picture. I note that the amounts and directions of dip as recorded in a number of sections in fig. 1 differ from those observed by me. For example, at 41/900372 I have measured a dip of 6° to the NNW. Nevertheless, however complicated these readings are there does appear to be other evidence of a north–south anticlinal stretching from the Gibbet Hill area northwards to the west of Thursley. Kirkaldy has suggested a monocline throwing to the west, but it is difficult to confirm this. The existence of a gentle fold, however, seems probable from the following observations:

(*a*) The Small Brook at Highcomb Bottom is fed by streams which arise only from the east. In this valley slumping has clearly only taken place on the eastern side in a westerly direction.

(*b*) The junction between the Hythe Beds and the underlying clay is higher by about fifty feet in Highcomb Bottom than to the east, south of Rutton Hill.

(*c*) Bargate doggers can be seen near St. Michael's Church, Thursley. Such characteristic stones have not been found, to my knowledge, so far north as in this area.

(*d*) As shown in fig. 1, it is also just along this north–south axis that the Folkestone Beds swing northwards for a short distance.

There is evidence of other flexures and I agree with the authors regarding their findings at Stock Farm and Green Cross pits and in the Small Brook, as stated on p. 231.

Another problem has been the mapping of the Hythe Bed–Bargate Bed junction. Contrary to the authors' field-work (p. 218) I have found large calcareous Bargate doggers at the southernmost part of the sunken lane leading to Upper Highfields (41/895378). The junction of the Hythe–Bargate Beds is here clearly seen to be just where the sudden physiographical drop to the north takes place. The junction to the west of Small Brook was also located just where this drop occurred, by means of surface features, as described well by the authors (p. 218). Hence my mapping implies a north–south trending fault, with a downthrow to the east, near Small Brook; the stream possibly flowing along a line of weakness, as emphasised by the gorge along this stretch.

I have drawn the Hythe–Bargate Beds junction, in Small Brook, a little farther north than shown in fig. 1, where I observed a yellowish plastic clay, about one inch thick, just below the Bargate Stones. The clay divides a light coloured sand below from a darker sand above. It is interesting to note that in 1894, Chapman similarly recorded, near Godalming (*Quart. J. geol. Soc. Lond.*, **50**, 687), a tough claylike Fuller's Earth in sand beds below the Bargate Stones up to four inches thick.

The authors mention (p. 232) that I mapped a fault to the west of Black Hanger. My reason for doing this is the nature of the various curious exposures seen around 41/900377. At the top of the minor road, forking off from the main Portsmouth Road, are characteristic Hythe Beds. We also find undoubted Hythe Beds, with unusual black chert, 1000 feet farther south. But in between these exposures are sections showing different rock types and which I could only recognise as belonging to the Bargate facies. Hence the mapping of a fault throwing Bargate Beds down to the east.

It is thus possible that because of these two faults, the outcrop of the Hythe–Bargate Beds junction has been so displaced, between Vanhurst Copse and Black Hanger, as to show no visible evidence of the north–south anticlinal.

It may be of value if I take this opportunity of placing on record some fossils found in this region, which have been kindly identified by Mr. C. P. Castell of the British Museum (Natural History):

At Stoke Farm Quarry, in Bargate Beds: *Exogyra conica* (J. de C. Sowerby), *Ostrea* sp., *Spondylus* sp.

Small Brook at 890377, in Hythe Beds: *Lima* (*Mantellum*) cf. *parallela* (J. Sowerby).

Brook Brickyard, western part of the brickyard, in Wealden: *Unio* sp., *Neomiodon* (*Cyrena*) *medius* (J. Sowerby), *Viviparus elongatus* (J. Sowerby), *Cypridea valdensis* (J. Sowerby).

Brook Brickyard, eastern part of the brickyard, Aptian, in ? Hythe Beds: *Astarte* cf. *subcostata* d'Orbigny, *Pholadomya cornueliana* d'Orbigny.

P. STRAUS,
17 *Stemdale Road,*
Long Eaton,
near Nottingham.

False bedding can certainly give a misleading picture of dip directions if not recognised as such. Fortunately in this area it can be distinguished fairly easily from true dip, the chief cause of differences of opinion over exact readings being the generally very low angle of the latter. The dip reading specifically mentioned by Mr. Straus was among those re-examined, and confirmed as shown on fig. 1, while the paper was in the press. The dip shown on fig. 1 in the Small Brook at 41/891378 as 19° is in error and should read 10°.

Mr. Straus' evidence for a north–south flexure north of Gibbet Hill is interesting but can be explained in other ways. In fact his points *b*, *c* and *d* are in accord with the interpretation given in the paper, and in that case it seems unnecessary to invoke such a major departure from the regional structural pattern as a cross-fold almost at right angles on the evidence of point *a* only. The preponderance of slumping on the eastern side of Highcomb Bottom could possibly be connected with the narrowness of the ridge of Hythe Beds along the Portsmouth Road which, because of the clay outcropping on both sides, has led to unusually extensive development here of superficial movement both eastwards and westwards.

For the suggested fault along the Small Brook there seems little evidence either way. We observed the Bargate doggers at 41/895378 but did not consider them to be *in situ*. The other suggested fault west of Blackhanger was discussed in the paper and it is undoubtably true that the exposures referred to by Mr. Straus show anomalous dip directions, but, after discussion with him, we re-examined them and were satisfied that they are of Hythe lithology.

We are very pleased to see published Mr. Straus' list of fossils, which forms a considerable addition to knowledge of these faunas.

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The Old Red Sandstone of the Cleobury Mortimer Area, Shropshire

by D. L. DINELEY and D. W. GOSSAGE

Received 27 May 1958; taken as read 5 June 1959

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ABSTRACT: The Lower Old Red Sandstone sequence in the area of the Cleobury Mortimer syncline is closely comparable with that in Corvedale. The 'Holdgate Sandstones' are recognised and it is shown that individual '*Psammosteus*' Limestones can locally be more accurately mapped by geophysical (resistivity) methods. White's ostracoderm zones are recognised and the unfossiliferous Breconian Clee Series is probably present. No Upper Old Red Sandstone has been detected.

The relationship of the syncline to the structure of the Clee Hills is briefly considered.

1. INTRODUCTION

PROBLEMS WHICH AROSE during a study of the Lower Old Red Sandstone of Brown Clee Hill by one of the writers (D.L.D.) were further investigated by the other at Cleobury Mortimer. This led to the joint mapping of an extended area south-east of Titterstone Clee Hill and the present paper indicates some of the results of that work.

Situated on the eastern slopes of Titterstone Clee Hill (Fig. 1), the area studied extends from the edge of the coalfield there to the Wyre Forest coalfield some four and a half miles to the east. The country lies between 400 and 900 feet O.D. and is drained by the southward-flowing River Rea and the Hopton or Mill Brook. Much of the structural 'grain' is reflected in minor topographical features and the smaller streams often flow in east–west strike valleys. The land is almost entirely given over to farming and is wooded only on the steeper slopes.

The dominant structural feature is the easterly plunging Cleobury Mortimer syncline (Fig. 2). A small outlier of Coal Measures (Kinlet Group), resting upon possible Breconian beds, lies near the axis of this fold at Cleobury Mortimer. Yellowish clay with abundant dolerite fragments obscures much of the solid geology on the slopes of Titterstone Clee Hill and masks a number of critical points. Exposures in the higher parts of the sequence are limited to discontinuous stream sections and a few overgrown quarries. Recent deep excavations along the line of the Elan Aqueduct have revealed much useful data.

This area was mapped by the Geological Survey prior to 1850, the results appearing in the (Old Series) One-inch Geological Sheets 55 NE. and 55 NW. The Old Red Sandstone was not subdivided on these maps but impersistent bands of 'cornstone' were shown. W. W. King mapped the district on the six-inch scale during the early decades of this century but his work was never published. More recently the Geological Survey carried out field work for the preparation of the Droitwich Sheet (New Series number 182) and brief references to the geology are given in the 'Summaries of Progress' for 1930, 1933 and 1937.

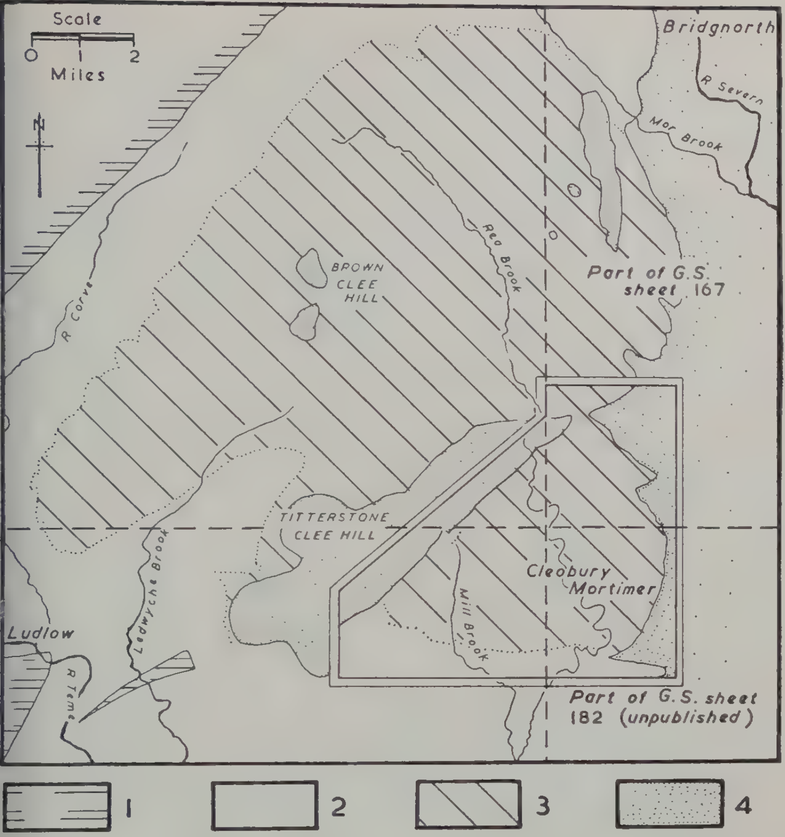
In the following account special attention has been paid to two aspects of the stratigraphy, namely, the position, continuity and number of the '*Psammosteus*' Limestones and the stratigraphical value of the ostracoderm faunas.

2. STRATIGRAPHY

Since the various Carboniferous formations of Titterstone Clee Hill are mentioned in the section on the structure of the present area, they are included in the stratigraphical table.

TIME UNITS		TIME-ROCK UNITS	ROCK UNITS	DOMINANT LITHOLOGIES	ZONE FOSSILS
CARBONIF.	*Ammanian*		Highley Group Kinlet Group		
	Namurian		Cornbrook Sandstone		
	Tournaisian		Carboniferous Limest		
DEVONIAN Old Red Sandstone Upper	*Farlovian*	Farlow Sandsts. Series		Grey and yellowish grits, sandstones and shales	
Lower	*Breconian*	Clee Series		Drab-grey and buff sandstones and shales	
			Abdon Limestone(s)	Concretionary limestone	
	Dittonian	Ditton Series	Ditton Group 1200 ft	Marls, calcareous sandstones and cornstones	*Pteraspis (Rhinopteraspis) leachi* *Protaspis crenulata* *Pteraspis crouchi*
	Downtonian	Downton Series	'Psammosteus' Lsts. phase 170–200 ft	Marls, calc sdsts, cornsts, concretionary limestones	*P (Protopteraspis) leathensis*
				Marls, sandstones and grits	*Traquairaspis symondsi* *Traquairaspis pococki*
			U Red Downton Formation 600–700 ft	Red marls	
			0–40 ft Holdgate Sdsts	Coarse, lenticular, calcareous sandstones	
			L. Red Downton Formation 500–600 ft	Red marls	
			Grey Downton Form'n Temeside Beds		
			Downton Castle Sandstone		
			Ludlow Bone Bed		
SILURIAN	*Ludlovian*	Ludlow Series			

For the present purpose it has been found convenient to retain the terms 'Downton Series' and 'Ditton Series' (see Ball & Dineley, 1952). The lower part of the Downton Series (i.e. the Grey Downton Formation) has not been examined and the upper boundary of the series is drawn on the



KEY:

1, Silurian; 2, Downton Series; 3, Ditton Series and higher Old Red Sandstone formations; 4, Carboniferous

Fig. 1. Sketch-map showing the location of the area described in this paper

map at the base of the local '*Psammosteus*' Limestone phase. This latter group of rocks appears to contain the Downtonian–Dittonian boundary as defined by White (1950, 56), and is discussed below (p. 226). Apart from these limestones, no further useful marker horizons have been found. The beds of fossiliferous sandstone and grit occurring near the base of the Ditton Series south of Cleobury Mortimer are distinctive and are probably continuous over a distance of a mile or more. They have not, however, been recognised on the northern flank of the syncline.

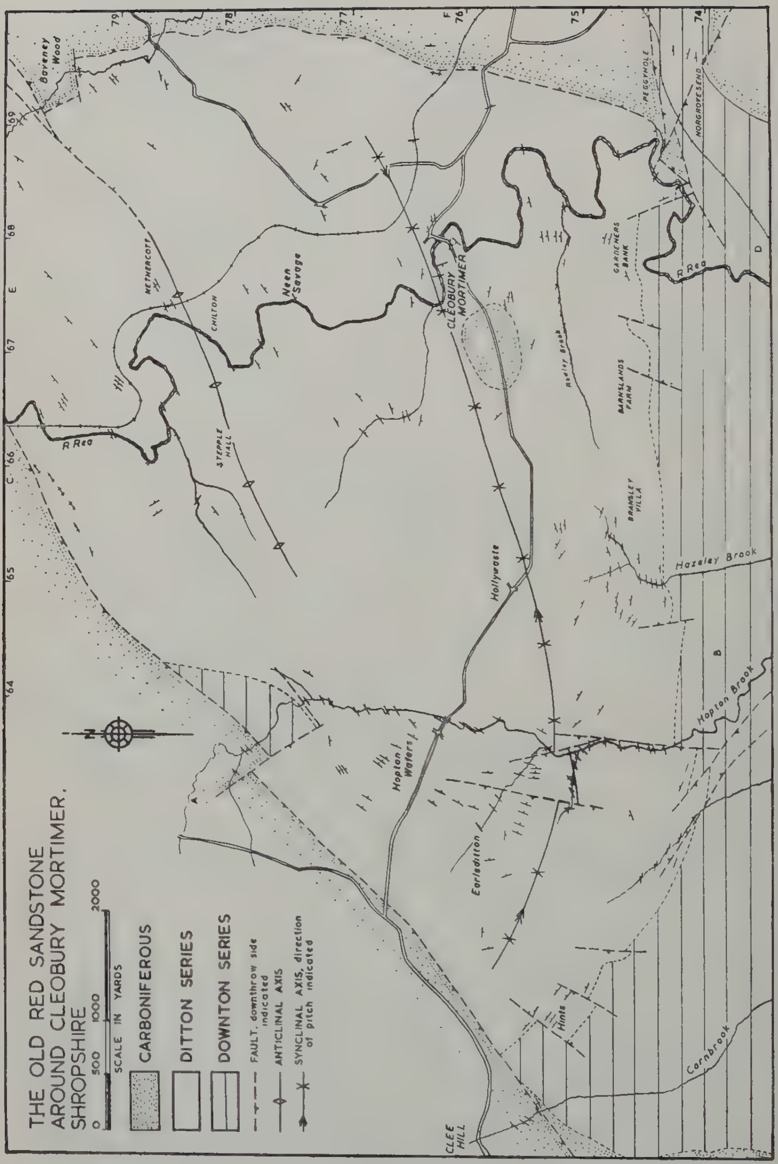

THE OLD RED SANDSTONE AROUND CLEOBURY MORTIMER, SHROPSHIRE
0
500
1000
2000
SCALE IN YARDS
CARBONIFEROUS
DITTON SERIES
DOWNTON SERIES
FAULT, downthrow side indicated
ANTICLINAL AXIS
SYNCLINAL AXIS, direction of pitch indicated
N
64
65
66
67
68
69
74
75
76
77
78
79
A
B
C
D
E
F
Bayeney Wood
NETHERCOTT
CHILTON
Neen Savage
R Rea
STEEPLE HALL
CLEOBURY MORTIMER
Hollywaste
Hopton Waters
Earlsditton
CLEE HILL
Hints
Cornbrook
Hopton Brook
Hazeley Brook
BRANSLEY VILLA
BARNSLANDS FARM
GARDENERS BANK
PEGGYHOLE
NORGROVESEND
R Rea

Fig. 2

(a) Downtonian

Downton Series: Red Downton Formation

(*i*) '*Holdgate Sandstones*'. In Corvedale the Downton Series is subdivided into two formations—Grey Downton Formation below and Red Downton Formation above. The latter may be traced in continuous outcrop into the present area but only the higher part of it is described here. Seven hundred feet or so below the base of the Ditton Series on the southern limb of the Cleobury Mortimer syncline is a group of coarse lenticular sandstones. On the grounds of their lithology and stratigraphical position they are correlated with the Holdgate Sandstones of Corvedale (Dinham, 1933, 45; Dineley, 1950, 134). They lie within soft red marls and give rise to prominent ridges and hillocks which can be followed from the western edge of the Wyre Forest coalfield to Hope Bagot. The maximum thickness attained by an individual sandstone there seems to be about twenty feet; laterally the bed may be traceable for several hundred yards.

The sandstones are composed chiefly of sub-angular quartz grains and small quartz pebbles; locally they are micaceous and some include considerable finely divided felspathic material. Other minerals present in small quantity include garnet, magnetite and tourmaline. The cement is largely calcareous and occasionally there is appreciable red iron oxide. In some exposures marl pellets are very numerous within the sandstone. Current-bedding is often visible. Fossils are very rare but include spines of '*Onchus*' and other acanthodians.

(*ii*) *The Upper Red Downton Formation*. The marls above the 'Holdgate Sandstones' give low-lying flat country and are typically massively bedded, soft and bright red or purple red, with occasional pale green bands, veins, joint surfaces and spherical blobs. A few bands of small calcareous nodules ('race') and rare thin sandstones are present here and there.

The top of the Downton Series is marked by the appearance of lenticular coarse bright red and green sandstones somewhat similar to the 'Holdgate Sandstone' and with *Traquairaspis* and other ostracoderms. The lowest of the '*Psammosteus*' Limestones occur within this group and should therefore be viewed as Downtonian in age. Higher '*Psammosteus*' Limestones within the ' "*Psammosteus*" Limestone phase' are more conveniently regarded as Dittonian. The palaeontology of the uppermost Downtonian beds is discussed below (p. 232).

(b) Dittonian

Ditton Series

This series consists of 1200 feet or more of rapidly alternating marls, sandstones and pellet conglomerates and includes part of the ' "*Psammosteus*" Limestone phase' at its base. The presence of the harder strata produces a higher terrain than the Downton Series and the numerous thick sandstones at the base of the series give rise locally to a scarp face of about 200 feet. The upper limit of the series remains unknown at Cleobury Mortimer.

The marls are closely similar to those of the Downton Series. Frequently, however, they are bluish or green, micaceous and often highly calcareous. The lithology of the sandstones is variable; they may be red, yellow, green or variegated. Grain size ranges from very fine siltstone to coarse and gritty. Calcareous cement locally produces small 'doggers' and lustre-mottling. Some beds are highly micaceous and also contain garnet. Many of the sandstones are clearly very lenticular while others may be traceable for distances of up to a mile. A basal pellety or cornstone layer is usually developed at the base of the thicker sandstones, especially those that rest upon eroded surfaces of marl. Current-bedding is very common and ranges in scale from very small to large (foreset beds one foot thick). The angle of the foreset beds to the major bedding planes is usually less than 15 degrees. Surface markings include ripples, (?) flow-casts, dubious desiccation cracks and rain-prints. Fish-remains occur in a number of the coarser beds while plant debris and eurypterids, though poorly preserved, are abundant in certain fine buff and green siltstones and shales. The cornstones are similarly very varied and include almost every gradation from near-limestones to pellet beds containing only a little calcareous matter. One or two include pellets of vegetable carbon and scattered quartz pebbles. Ostracoderm remains are most commonly found in rocks of this lithology, especially where strongly current-bedded and resting on erosion surfaces.

Concretionary limestones are present at a number of levels but of these only the '*Psammosteus*' Limestones are sufficiently persistent to be of use in the field.

(*i*) *The* '*Psammosteus*' *Limestones.* Several opinions have been expressed in the past regarding the stratigraphical continuity and position of the '*Psammosteus*' Limestones. While most writers have acknowledged the fact that there may be several distinct limestones within the '"*Psammosteus*" Limestone phase', frequent reference has been made to a single limestone (presumably the thickest, most distinct or widespread in the particular area discussed). W. W. King (1925, 1934) included several such limestones within the 170 feet of his stage I 8, yet his maps often show only one continuous limestone. Work around Brown Clee Hill suggests that over wide areas one main '*Psammosteus*' Limestone is developed while others often occur above or below it (Ball & Dineley, 1952). This does not imply, however, that such is the case throughout the entire Anglo–Welsh area.

White (1950, 52) suggested that the '"*Psammosteus*" Limestone phase' is diachronic, but as Whittard points out (1952, 177), he means that the limestones are present at varying levels from within the zone of *Traquairaspis symondsi* Lankester to within that of *Pteraspis* (*Protopteraspis*) *leathensis* White. The limestones probably formed only when certain chemical conditions prevailed (they are completely inorganic) and are 'probably not strictly speaking diachronic, that is, in the original meaning of Wright. . . .' (Whittard, *op. cit.*). Krumbein & Sloss (1951, 313) remark that 'Individual limestone units in sequences of other lithologies represent conditions which presumably were of essentially simultaneous effect over much of a sedimentary province'. Some of the larger exposures and detailed mapping in the Clee Hill area show every reason for considering that the individual '*Psammosteus*' Limestones are 'time-parallel' units, even though their continuity over the entire area may not be proved. Obviously in a group of lenticular, rapidly alternating and generally unfossiliferous strata such as the Lower Old Red Sandstone time-parallel marker horizons are of the greatest value in the correlation of fossil-bearing sections. The visible field evidence is, however, normally insufficient to decide whether or not one or other of the '*Psammosteus*' Limestones is such an horizon.

With this in mind, special attention was paid to the mapping of the '*Psammosteus*' Limestones near Cleobury Mortimer. The available evidence has been collected from some five miles of outcrop, but the problem appears to call for field examination reaching over the greater part of the Anglo–Welsh area. From the local data it seems that at least some of the limestones are very lenticular. Three closely adjacent sections (Fig. 3) show remarkably different sequences and little information concerning the behaviour of the limestones in the intervening ground was at first available. To investigate this ground several shallow excavations were made to determine the presence of the beds and resistivity traverses were also carried out.

As a rule, the limestone is not very porous and may be expected to have a correspondingly high resistivity. Using the standard Gish-Rooney electrode system (Bruckshaw, 1948, text-fig. 8), with electrodes connected to a 'Megger' earth-tester, an electrode line was arranged roughly parallel to the strike. An electrode separation of approximately five feet ensured a penetration of the same amount. Readings were taken at regular intervals (usually ten feet or less) along a dip traverse. A test traverse was first run over the strata exposed in a landslip scar at Gardeners Bank. A second traverse was then made over the ground between two limestone quarries just west of Barnslands Farm. On the usual field evidence the presence of the limestone there is beyond doubt. Resistivity readings were taken at intervals of five feet. The results are shown graphically in Fig. 4.

These traverses show a resistivity peak corresponding with the limestone and smaller anomalies for the sandstones, and the method seemed to indicate possibilities as far as the limestone was concerned. Subsequent excavations at points where the limestone was indicated by resistivity work have proved the presence of that material, though cornstones sometimes produce similar resistivity effects. A number of traverses were made across the escarpment between Gardeners Bank and Bransley Villa.

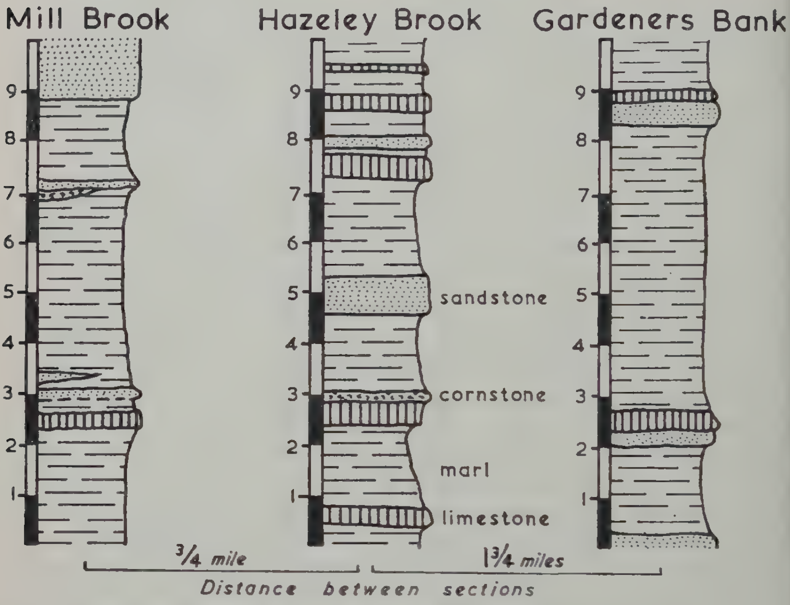


Fig. 3. Three closely adjacent sections through the '*Psammosteus*' Limestones south of Cleobury Mortimer

The measured resistivities have been plotted as double histograms on the map (Fig. 5). The greatest increases in resistivity were usually found where the limestones were already expected from other evidence (e.g. on traverses, 3, 5, 8, 9 and 10). On traverses or parts of traverses where the positions of the limestones were unknown (1, 2, 6, 7 and 11) outcrops have been drawn passing through the points of highest resistivity. Less prominent increases are probably the effects of calcareous sandstones, 'race' bands or very thin limestones. The resistivity of cornstones is also often high, but there is little evidence that these rocks are present within the limited area studied. Variations in overall resistivity value may be due to variations in the thickness of the soil, water content in bedrock and soil and the thicknesses of the different beds.

Visible and geophysical evidence combined have thus been used to plot the outcrops of individual '*Psammosteus*' Limestones over a small stretch

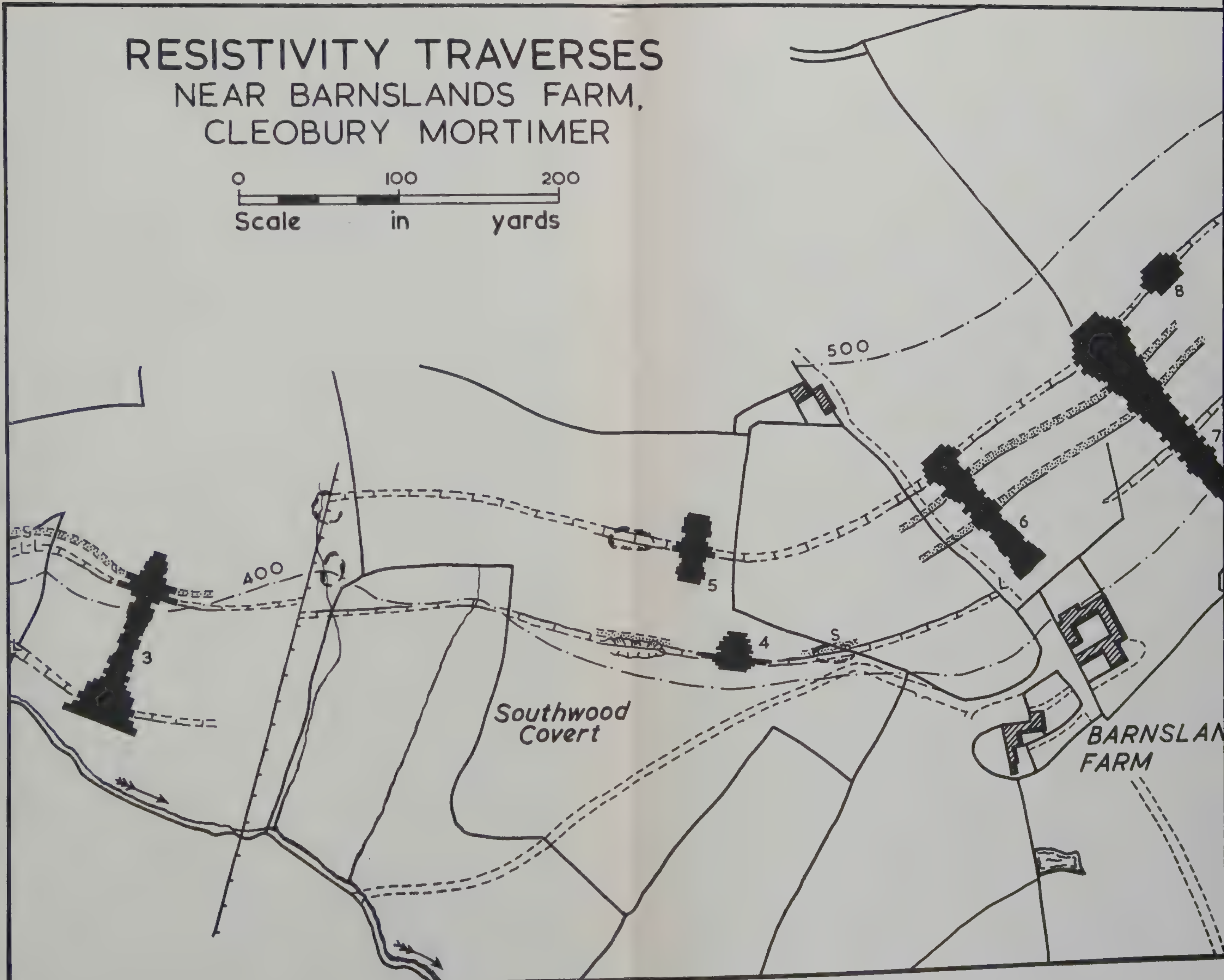

RESISTIVITY TRAVERSES
NEAR BARNSLANDS FARM,
CLEOBURY MORTIMER
0
100
200
Scale in yards
8
500
7
6
5
400
4
3
S
S
Southwood Covert
BARNSLAN
FARM

Fig. 5

of ground. It is observed that one limestone is traceable over at least a mile and a half; less persistent limestones lie above and below this 'main' limestone. The lithologies of these beds vary laterally from massive to rubbly within short distances. It has not been possible to determine if this 'main' limestone is identical with that at Hazeley and Hopton Brooks, and it is not known if it is continuous with the main limestone in southern Corvedale. Nevertheless, one of the authors (D.L.D.) has been able to use with success this resistivity technique in tracing the outcrop of limestones in Corvedale and at Monkhopton near Brown Clee Hill. On the western flanks of Titterstone Clee Hill the results are rendered unsatisfactory by the presence of a heavy mantle of superficial material. The number and continuity of the '*Psammosteus*' Limestones there is still open to doubt.

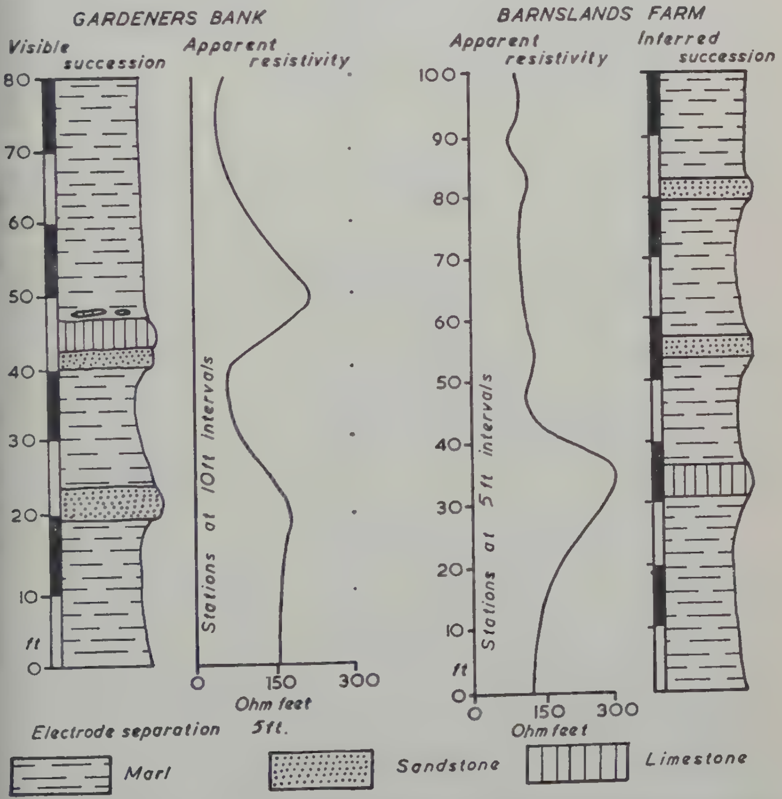


Fig. 4. Resistivity traverses over 'known ground' at Gardeners Bank and Barnslands Farm

(*ii*) *The Ditton Group.* The 1200 feet or more of rapidly alternating marls, sandstones and cornstones above the limestones resemble in every respect the Ditton Series in the Brown Clee Hill area, except in that the proportion of sandstones and cornstones in the sequence seems to be somewhat smaller. At Brown Clee the figure is approximately 40 per cent in the lowest 400 feet of the series, slightly less above; in the exposures of the Cleobury, Hopton, Mill and Hazeley Brooks it is only about 22 per cent for the lower half of the series. Exposures are not frequent enough to give a figure for the upper part of the series at Cleobury Mortimer.

Fig. 6 gives diagrammatically the sequences recorded in the Hopton Brook.

The highest parts of the Ditton Group show generally grey, yellowish and buff colours predominating. The marls are inclined to be silty and purple or bluish in colour. In the sequence at Rowley Brook these beds consist for the most part of sandstones and cornstones. It is not possible to fix a boundary between these and the redder beds below as there seems to be a gentle gradation between the two types. Moreover, the Rowley Brook affords almost the only continuous exposure through this part of the succession.

(*iii*) *Palaeontology.* In the Clee Hill area the following Downtonian–Dittonian 'fish' zones are recognised (White, 1956).

TABLE II

LOWER DEVONIAN	DITTONIAN	*Pteraspis* (*Rhinopteraspis*) *leachi* White and *Protaspis crenulata* White MS	Lower Siegenian	LOWER DEVONIAN
		Pteraspis (*Belgicaspis*) *crouchi* Lank. and *Pteraspis rostrata* (Ag.) *Pteraspis* (*Protopteraspis*) *leathensis* White	Upper Gedinnian	
	DOWNTONIAN	*Traquairaspis symondsi* (Lank.) *Traquairaspis pococki* White (not found at Brown Clee)	Lower Gedinnian	

The fossils occur in the cornstones and sandstones and are usually fragmentary. Extracting them from the rock is a laborious business. The Traquairaspids are identified with comparative ease since even the smallest fragments usually preserve the distinctive ornamentation. The identification of the Pteraspids is by no means so readily made. Preservation is usually poor, the 'carapaces' being commonly incomplete. Identification can only be certain when the greater part of the carapace is present, though some forms (*Rhinopteraspis*) bear distinctive surface ornamentation. As now

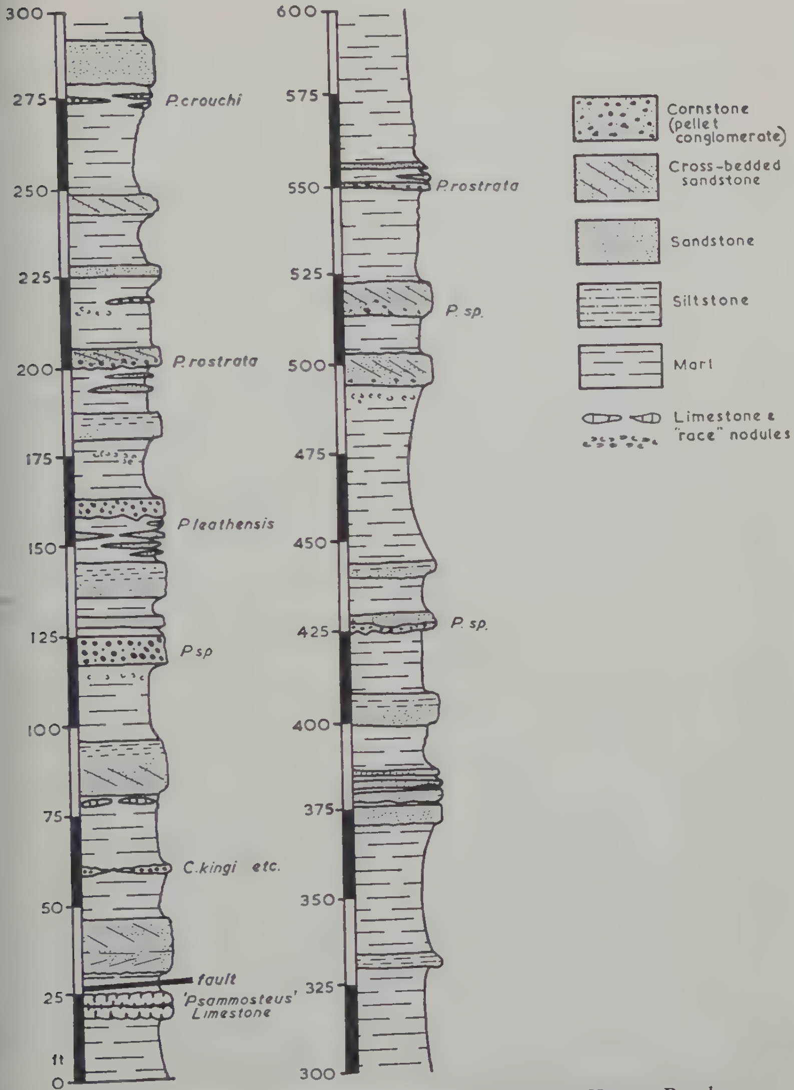


Fig. 6. Section through the Ditton Series exposed in Hopton Brook

seems general in the Lower Old Red Sandstone of the Welsh Borderlands, the vertebrate remains appear to be more or less local and water-sorted thanatocenose accumulations. (Further discussion of this topic will appear in a future paper by one of the present authors.) It is difficult to establish if reworking of the fossils over appreciable stratigraphical intervals occurs, but for various reasons it is not thought likely.

The stratigraphical ranges of some of the zonal species are now known to overlap to a small degree. Near Clifton-on-Teme the two species of *Traquairaspis* occur in the same bed. In the Clee Hills *T. symondsi* has been found with *Pteraspis*, and *P.* (*Pr.*) *leathensis* occurs with the larger pteraspids. Nevertheless, it is abundantly clear that White's zones are of very real value and the instances mentioned above in no way diminish this. In the Cleobury Mortimer area the thirty-six fossiliferous localities found serve to emphasise the stratigraphical significance of the zones. No overlap of the *Pteraspis* species is observed, but some overlap of the *Traquairaspis* ranges seems to be indicated. *T. pococki* is found seventeen feet below the 'main' '*Psammosteus*' Limestone and *T. symondsi* occurs 100 feet below what on geophysical evidence appears to be the same limestone. The well-known exposures at Gardeners Bank and Reaside Farm (White, 1946, 209; 1950, 55) clearly show *T. symondsi* succeeding *T. pococki*, and further occurrences of these two species maintain the same relationship. Immediately below what is regarded as the 'main' '*Psammosteus*' Limestone *T. pococki* is common, while above it *T. symondsi* is present.

Small forms of *Pteraspis*, regarded as *P. leathensis*, appear above the limestones and occur as high as 250 feet above the lower '*Psammosteus*' Limestone in Hopton Brook. The lowest horizon at which *P.* (*B.*) *crouchi* has been found is some 300 feet above the base of the Ditton Series (as mapped in the field) and it extends upwards to about 900 feet above the base of the Series. From one horizon yielding *P.* (*B.*) *crouchi*, a new and distinctive species of *Pteraspis* (at present being described by Dr. E. I. White) has also been collected. *Pteraspis rostrata* has been found only within the beds from 600 to 850 feet above the base of the Series.

The Rowley Brook exposures were regarded by the Geological Survey as being Upper Old Red Sandstone (Dinham, 1933) but the fossils from there are now known to have been erroneously identified. *Pteraspis* (*Rhinopteris*) sp. and *Protaspis crenulata* are now recorded from horizons within these beds, estimated to be approximately 1100 feet high in the Ditton Series. No Upper Old Red Sandstone fossils have been found.

Apart from the fossils mentioned above, the following, represented mainly by fragments, have been collected but their full stratigraphical significance cannot yet be assessed.

? Arctolepids (probably several spp.: only a few fragments)
Anglaspis macculloughi Woodward (common in ' "*Psammosteus*" Limestone phase')
Cephalaspids including *Didymaspis grindrodi* Lank. (rare)
Corvaspis kingi Woodward (found only at three localities in ' "*P.*" L. phase')
'*Ischnacanthus kingi*' Woodward (found at several localities)

Onchus spp. (at several horizons)
Kallostrakon sp. (confined to a very few beds low in the Dittonian and in the Downtonian)
Spines indet.
Tesseraspis tessellata Wills (known at a few levels in ' "*P.*" L. phase')
Thelodont denticles (surprisingly numerous in several Dittonian beds).

A list with details of the fossiliferous localities is deposited in the Geological Department, University of Birmingham, and also in the Department of Palaeontology, British Museum (Natural History).

(c) Breconian

Clee Series

In the Brown Clee Hill the Clee Series follows conformably upon the Ditton Series, its base being marked by the Lower Abdon Limestone. The Clee Series has not been identified with certainty in the Cleobury Mortimer syncline; but coarse and medium grained rocks, similar to those of the Clee Series, are sometimes excavated below the streets of Cleobury Mortimer. Similar sandstones appear to be present around Hollywaste. No fossils have been found nor have the Abdon Limestone or its associated calcareous sandstones been located. (The Clee Series is not indicated on the map.)

3. STRUCTURE

(a) Folds

The asymmetrical, roughly boat-shaped Cleobury Mortimer syncline is the dominant structural feature of the area. At Cleobury Mortimer the fold trends east-north-east but swings to the east at Hopton Brook and south-east at Hints. On the southern limb dips average 43°. Dips on the northern limb are variable due to complications in structure around Hopton Wafers. North of Cleobury Mortimer, where there is least disturbance, the dip is about 16°. At the western end of the syncline the axis plunges east at somewhat under 35° but to the east of Cleobury Mortimer the westerly plunge is 10° or less.

On the northern side of the syncline the Neen Savage anticline can be traced for at least two miles, plunging to the east. At Overwood Common its axis strikes north-east while between Chilton and Stepple Hill it is roughly parallel to the synclinal axis at Cleobury Mortimer. North and west of Hopton Wafers there are important deviations from the east–west strike. In the vicinity of Earlsditton the strike swings gradually round to north-west as if to close the syncline. Exposures in the northern part of Hopton Brook show a swing in strike towards the north-east. Here a further outcrop of the '*Psammosteus*' Limestones and Downtonian marls suggests that an anticlinal is present below the eastern end of the synclinally folded Titterstone Clee coalfield. This may be comparable to and associated with the horst-like inlier of Silurian rocks at Caynham, five miles to the south-west on the line of the Titterstone Clee syncline. (See Elles & Slater, 1906, map.)

The map of Bouguer anomalies in the West Midlands by Cook and others (Cook, Hospers, Parasnis, 1952, pl. XVIII, fig. 2) shows a positive anomaly of six or more milligals in the present area with a small peak of eight milligals just south of Cleobury Mortimer and an elongated ridge in the Neen Savage–Kinlet area. These probably correspond to the anticlinal structures between Cleobury Mortimer and Neen Sollars, where Silurian rocks outcrop, and at Kinlet where Coal Measures and igneous rocks are involved. The depression between these 'highs' appears to reflect the Cleobury Mortimer syncline.

At a number of localities small disturbances, comparable with drag folds, have been found and no doubt arise from the folding of the rapidly alternating sequence of competent and incompetent strata in the Ditton Series.

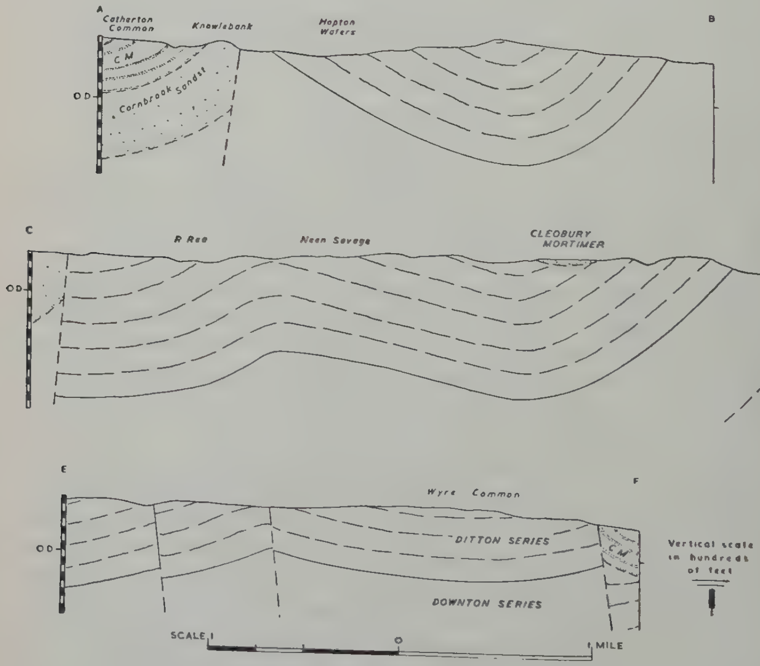


Fig. 7. Sections through the Cleobury Mortimer area
(The points A–F are indicated on the map, Fig 2)

(b) Faults

The absence of usable marker horizons above the '*Psammosteus*' Limestones makes the tracing of faults in the Ditton Series difficult. Nevertheless, several important faults are suspected, and appear generally to be dip-slip faults.

A large fracture runs approximately along the line of Mill Brook where lateral movement has displaced the synclinal axis about 300 yards southwards on the west side. A series of small faults affects the '*Psammosteus*' Limestones outcrop west of Mill Brook, each one except the Hints fault downthrowing to the west and trending obliquely to the strike. A small almost northerly fault appears to run between Hopton Wafers and Earlsditton, where a larger fault, striking north-west from near Stock Hall, affects both Old Red Sandstone and Carboniferous near Catherton Common.

The eastern end of the Neen Savage anticlinal axis appears to merge with a strong fault mapped by the Geological Survey from Nethercott north-eastwards to Kinlet Park and beyond. Its downthrow is to the south and brings in the Coal Measures in the vicinity of Baveney Wood.

(c) Old Red Sandstone–Carboniferous Boundaries

The eastern boundary of the Titterstone Clee coalfield has generally been considered to be faulted since it follows an approximately straight course north-eastwards from Cornbrook Dingle to join the Brock Hall faults near Kinlet Park. In Cornbrook Dingle only the Carboniferous outcrop is affected; the Carboniferous Limestone on the southern side of the fault rests unconformably on red Downtonian marls. Trial boreholes put down across the line of the fault west of Doddington some years ago revealed the higher beds of the Coal Measures faulted against Old Red Sandstone, a condition persisting north-eastwards as far as Catherton Marshes. At several points ancient coal-workings lie within a few yards of exposures of Old Red Sandstone. Near Knowlebank a transverse fault displaces the main boundary fault slightly to the south-east.

The small outlier of the Kinlet Group at Cleobury Mortimer is assumed to rest unconformably upon the Old Red Sandstone.

At the western limit of the Wyre Forest coalfield the Kinlet Group is in both faulted and unconformable contact with the Old Red Sandstone. From Bayton and Malpass Wood the junction runs nearly straight and there are local signs of faulting. Around Norgrovesend Farm the boundary is deeply indented to the east. This arises from two large faults, one running almost north-east through Peggyhole and downthrowing to the north, and the other trending west-north-west downthrowing to the south near Norgrovesend Farm. The combined effect of the two faults is responsible for the triangular Kinlet Group outcrop south of Lower Forge.

(d) Tectonic History

The tectonic history of the present area is directly related to that of the Titterstone Clee Hill coalfield area and the following includes a discussion of this wider topic.

Deposition appears to have been unbroken from Silurian to Breconian times but prior to the deposition of the Farlovian rocks there was flexuring, faulting and erosion. The effects of these earth-movements will shortly be described in detail by Dr. H. W. Ball. The dominantly Caledonoid trend of the major folds at Brown Clee, Ludlow and the Ledwyche Valley and Titterstone Clee Hill suggests that they were at least initiated during the post-Breconian pre-Farlovian interval. (The Caynham structure probably also dates from that time.)

At the end of Farlovian times minor earth-movements occurred, for the Tournaisian with a thin but conspicuous basal conglomerate rests unconformably upon Downtonian marls at Knowle and upon Upper Old Red Sandstone at Farlow.

George (1956) has claimed that the higher Dinantian rocks are missing at Titterstone Clee Hill and has shown that the Cornbrook Sandstone, which he considers to be Namurian, oversteps on to the Old Red Sandstone. The overstep of the Cornbrook Sandstone across the Dinantian Carboniferous Limestone indicates that the Titterstone Clee Hill 'once occupied part of a northern extension, or northern homologue of the Namurian Usk fold' (*op. cit.*, 297). Between Knowle and Clee Hill village the Carboniferous Limestone is sharply folded into a northwards-striking syncline with dips of 35° or more. This folding appears to affect the Cornbrook Sandstone to a lesser extent and the overlying Coal Measures only very slightly, if at all.

In Ammanian times the Kinlet Group was thus deposited upon a surface of earlier Carboniferous and Old Red Sandstone rocks which had suffered folding or warping at two different times at least: viz. (i) during ? Middle Old Red Sandstone times when a strong north-easterly component was developed, and (ii) during Lower-Middle Carboniferous times when a northerly component was produced. The succeeding Highley Group at Bayton, seven miles to the east-south-east, overlaps on to the Downtonian but is not preserved at Clee Hill.

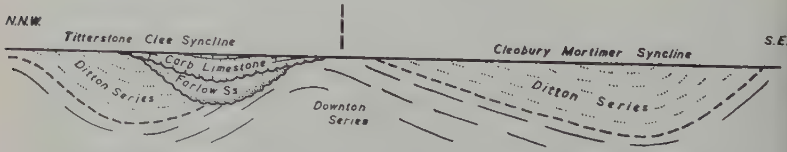


Fig. 8. Diagrammatic section to show structure of the Titterstone Clee–Cleobury Mortimer area in Namurian times

Post-Ammanian history is less easy to decipher. At one stage the later Carboniferous rocks of the Clee Hills were folded along previous lines. It may be significant that the Brown Clee, Titterstone Clee and Cleobury Mortimer synclines all have their steeper limbs to the south or south-east and that dips are much smaller in the northern part of the Clee Hills area. This suggests, in fact, that the folds were simultaneously produced by compression from the south or south-east. The more 'Armoricanoid' trend of the Cleobury Mortimer syncline may result also from the Carboniferous movements at Titterstone Clee Hill.

Fault movements after the deposition of the Coal Measures often seem to have been strongly influenced by the existing folds. The eastern boundary fault of the Titterstone Clee Hill coalfield separates the more 'Caledonoid' folds to the west from the more 'Armoricanoid' folds to the east. To the south this fault is undoubtedly associated with the Caynham structure (Elles & Slater, 1906) while to the north it seems to be connected with faults traversing the Wyre Forest coalfield. Towards the north-east the axis of the Neen Savage anticline appears to be replaced by a fault or faults also running north-eastwards into the coalfield.

4. CONCLUSIONS

The lithologies, depositional features and succession of the Lower Old Red Sandstone of the Cleobury Mortimer area compare very closely with those of rocks of the same age in Corvedale. The Holdgate Sandstones appear to be represented, though their direct continuity with those in Corvedale has not been established by mapping. There are several '*Psammosteus*' Limestones at or near the base of the Ditton Series, and these possess a higher apparent resistivity than the enclosing strata. This property has been used to determine the continuity or presence of the limestones in ground south of Cleobury Mortimer, and has also been successfully employed around Brown Clee Hill. One limestone south of Cleobury Mortimer has been traced laterally over a distance of one and a half miles. The proportion of sandstones and cornstones to marl in the lower part of the Ditton Series appears to be about 20 per cent, which is slightly less than around Brown Clee Hill. No usable marker horizons have been found within the Ditton Series.

The faunas indicate that White's ostracoderm zones of *Traquairaspis* and the Pteraspids may be recognised in the area. Some overlap of the zonal forms can be demonstrated, but it is very small. No Upper Old Red Sandstone is indicated, though the Breconian Clee Series is possibly present.

The principal structure is a trough striking almost east through Cleobury Mortimer. Earth-movements of both pre- and post-Carboniferous (Ammanian) date are postulated, the later movements possibly having served to emphasise structures already existing in the Old Red Sandstone prior to the deposition of the Carboniferous.

ACKNOWLEDGMENTS

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The Clays and Heavy Minerals of the Shotover Ironsand Series

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ABSTRACT: Clays from the Shotover Ironsand series of Oxfordshire and Buckinghamshire have been examined by Differential Thermal Analysis techniques and their Base Exchange Capacities have also been determined. The results indicate that they are typical fireclays, the principal clay mineral present being a member of the kaolin family, illite probably also being present in some examples.

The heavy minerals of the Shotover Ironsands are chiefly zircon, tourmaline, rutile, kyanite, staurolite, limonite and leucoxene, with smaller amounts of sillimanite, garnet and anatase. This suite is similar to that of the Upper Jurassic rocks of the region, and it is suggested that reworking of these Jurassic rocks has provided the raw material for the formation of the Shotover Ironsands. The suite differs from published descriptions of heavy minerals from Wealden sands.

1. INTRODUCTION

THE SHOTOVER IRONSANDS consist of a series of vari-coloured sands, silts and clays, represented by a number of small outliers between the towns of Oxford and Aylesbury. The name is taken from Shotover Hill, between Headington and Wheatley, Oxfordshire, where the series reaches its maximum vertical development (about sixty feet), and where at one time it was well exposed as a result of excavations for iron ore, ochre and other products. Similar material was also worked at Brill, Quainton and Muswell Hill, Buckinghamshire, and has been exposed at several other places, such as Great Haseley, as a consequence of quarrying operations into the underlying Portland building stone.

It is not certain how ancient these workings are, but it is known that the ochre from Shotover was held in high esteem in the seventeenth century. Smith in 1800–5 mapped the beds and identified them with the 'Ironsands' of Wilts, Kent and Sussex. Since that time the literature on the Shotover Ironsands has been enlarged by Conybeare, Fitton, Phillips, Morley

Davies, Lamplugh, Prestwich, Arkell and others. Arkell, in addition to his original contributions, provides in the *Geology of Oxford* (1947) the most recent and extensive summary so far published of the evidence concerning the age, origin and distribution of the Shotover Ironsands, with a full bibliography.

Without reiterating all the arguments involved it may be said here that the beds are considered to be of fresh-water origin and that their age is equivalent to some part of the Wealden, perhaps to the Hastings beds. They lie unconformably on Kimeridge, Portland and Purbeck strata, and are in turn transgressed in places by sands of Upper Aptian or Lower Albian age.

In the course of some general investigations into the distribution and petrography of these beds in 1952–3 the present writer collected a number of samples for laboratory examination. Although this work added little to what was already known about the age or origin of the Shotover series it is felt to be worth publishing an account of the findings concerning the nature of the clays and the heavy minerals of the sands, as neither of these aspects has been described in the past.

Unfortunately the numerous workings in the Ironsands which attracted the attention of the earlier geologists have long ago fallen into disuse; many have been filled in and ploughed over, while others are completely overgrown. The only exposed sections which could be examined at the time that the writer was in the field were a small cutting exposing the base of the series and the underlying Portland stone near the track leading from Shotover Common into Horspath village, and the sand-pits on the north side of the village of Stone in Buckinghamshire, which are still in use. Practically all the field study and collection of samples was therefore carried out by augering. Samples were generally collected from depths of three to twelve feet according to the thickness of the soil and drift cover. The accompanying map (Fig. 1) shows the distribution of the series. West of Thame, Arkell's interpretation is adopted; the remainder follows the Geological Survey Old Series One Inch maps, No. 45 SE. and 46 SW., with modification by the writer.

2. GENERAL LITHOLOGY

Some general remarks on the lithology of the Shotover Ironsands are included here in order to correct an impression created by the name itself, which puts an undue emphasis on 'iron' and 'sand'. On Shotover Hill about a fifth of the succession is made up of clay. On other outliers the ratio is higher, and there may be as much clay as sand. In addition to this the sands themselves are not everywhere highly ferruginous, although locally they may be. Beds of sandstone cemented with limonite, and bands and box-like concretions of hematite, with decomposition to limonite, are

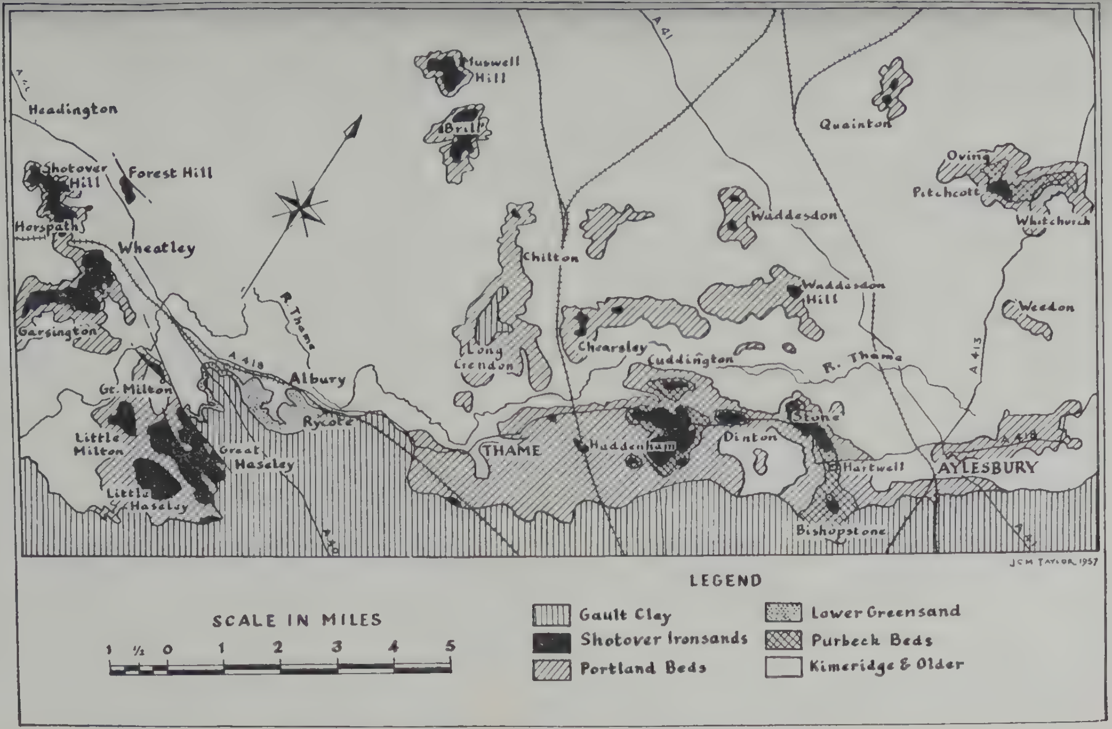

Fig. 1. Map showing the distribution of the Shotover Ironsands

found at intervals throughout the sequence, but such layers are usually thin, so that while typical of the Shotover beds, their relative bulk is small. The remaining unconsolidated sands are often brightly coloured in various shades of yellow, orange and red, in a way which clearly demonstrates the presence of iron compounds, but a large part of the series is made up of pale cream, grey and especially white sands and silts.

All the observers who have recorded sections of exposures once visible in the Shotover series have noted the variability of the beds as regards thickness and lateral extent. The workable beds of ochre and iron ore seem to have occurred at comparable horizons in different pits, but the accompanying beds described are quite different in detail from one pit to another. The lenticular nature of the bedding is noted in the Survey Memoir, and by Phillips (1871). Much slipping has occurred on the steeper hill-sides. These facts combine to make the correlation of individual beds from one locality to another difficult, if not impossible, and so preclude the areal study of petrological variations within any particular horizon. Samples were therefore collected from various outliers and from various heights above the base of the series with the aim of representing the series as a whole. As the field and laboratory evidence suggested no significant progressive changes in lithology or mineralogy, either vertically or laterally, this method seems to be justified.

One expression of the variability of the strata is that individual beds are rarely more than three or four feet thick, and quite often only as many inches. Under these circumstances it is never certain whether samples collected by augering represent one bed or several. For this reason measurements of particle size and sorting have no very clear meaning, and such data are therefore omitted from this paper. To give some idea of the range of sizes of the Shotover Ironsands, however, it may be mentioned that the coarsest sands encountered were found to have a median diameter of about half a millimetre, but most of the sand samples were very much finer than this, with a median diameter nearer one eighth of a millimetre.

In summary, perhaps the most consistent characteristic of the Shotover Ironsands is their variability. This variability serves to differentiate them in the field from the far more uniformly iron-stained and coarser marine Lower Greensand, with which there has in the past been some confusion. The non-calcareous nature of the Shotover Ironsands serves to distinguish them, where necessary, from the generally calcareous clays, marly sands, and limestones of the Purbeck strata.

3. CLAY MINERALS

As mentioned above, beds of clay form an important part of the Shotover Ironsand series. These clays vary considerably in colour, including shades of yellow, orange, red, brown, grey and occasionally almost black. One of the characteristics of the series, however, is the frequent occurrence of very light grey to pure white clays. Occasional mention in the older literature of 'fuller's earth' in the Shotover beds was regarded with interest in view of the known fuller's earth deposits of the Lower Cretaceous of Bedfordshire, but none of the clays examined in the field over the whole area resembled fuller's earth as the term is used today (i.e. of clays containing an abundance of montmorillonite or related 3-layer minerals), since when wet they do not swell or crumble but become plastic and sticky.

Laboratory examination of typical clay samples consisted of (1) preliminary microscopic examination, (2) Differential Thermal Analysis and (3) determination of Base Exchange Capacity.

(a) Microscopic Examination

Portions of all clay samples were dispersed by boiling with dilute sodium carbonate or ammonia, and washed through a 200-mesh sieve. The material retained (larger than 76 microns) was examined under a binocular microscope. No micro-fauna of any kind was observed. In all cases the residue consisted almost entirely of fine quartz sand, with varying amounts of hematite grains and muscovite. Small spheres of spherulitic siderite were present in one sample.

The heavy minerals were separated from the over-200-mesh fraction of one clay sample from Shotover Hill and found to be similar to those of the sands (q.v.).

Examination of the fraction passing 200 mesh, under the petrological microscope, showed an abundance of very fine quartz. The clay particles themselves were too fine for optical determinations.

(b) Differential Thermal Analysis

The principles and practice of Differential Thermal Analysis (D.T.A.) as applied to the study of clays are now widely known, and covered by an extensive literature. The subject has recently been conveniently summarised by R. C. Mackenzie (1957).

The type of apparatus used by the writer has the form of double crucible and crucible holder manufactured by the Thermal Syndicate to the design of Grimshaw and Roberts. The platinum-wound alumina furnace tube is supplied via a manually controlled resistance to give a heating rate of about 10° C. rise per minute. A platinum/platinum-rhodium thermocouple with hot junctions in the two compartments of the crucible is connected so as to provide simultaneous measures of the temperature of the inert material and the differential temperature between it and the material being examined. The temperature of the inert material is indicated on a sensitive galvanometer. The differential temperature is amplified by a D.C. amplifier and recorded continuously on a drum-type recorder. Provision is made for marking the temperature of the inert material on the chart at suitable intervals, so that a plot of differential temperature against absolute temperature is obtainable. Further details of this type of apparatus, together with the method used to redraw the curves in order to overcome the effects of uneven heating rate and 'drift', are described in the paper by Grimshaw, Heaton & Roberts, 1945.

Calcined alumina was at first used as the inert reference material in the tests, but better results were obtained by using a calcined mixture of clays from the Shotover series itself.

Differential thermal curves obtained for a number of samples from the Shotover series at various localities are shown in Fig. 2. The first obvious feature of these curves is a strong family likeness. Their principal characteristics are:

(a) A moderate double endothermic peak between 100° and 200° C.
(b) A pronounced, rather sharp peak in the region of 550° C.
(c) A very slight endothermic peak just below 900°, followed by a small exothermic peak at about 950° C.

The actual positions of these peaks could be the result of the presence either of illite, or the mineral (or series of minerals) intermediate in properties between kaolinite and halloysite which has been called by Brindley & Robinson (1947), 'the fireclay mineral'. The importance of the endothermic peak at 550° as compared with that between 100° and 200° C. suggests, however, that of these alternatives the fireclay mineral is the more likely.

Sample No. 7 is a highly ochreous clay, and the presence of limonite is indicated by the endothermic reaction at 300° C. The slight exothermic hump in the region of 300° in most samples is probably due to small quantities of carbonaceous matter.

(c) Base Exchange Capacity

The base exchange capacity of clays is often helpful in determining the groups of clay minerals present. Typical figures for the three principal groups of clays, expressed in milli-equivalents of exchangeable cation per hundred grammes of dry clay are:

Kaolinites	0–15 me/100 gm.
Illites	20–40 me/100 gm.
Montmorillonites	60–100 me/100 gm.

(See, for instance, W. P. Kelley, 1939, and R. E. Grim, 1939.)

Departures from these ranges are, however, known.

Numerous methods for determining base exchange capacity have been described in a voluminous literature. The determinations in the present

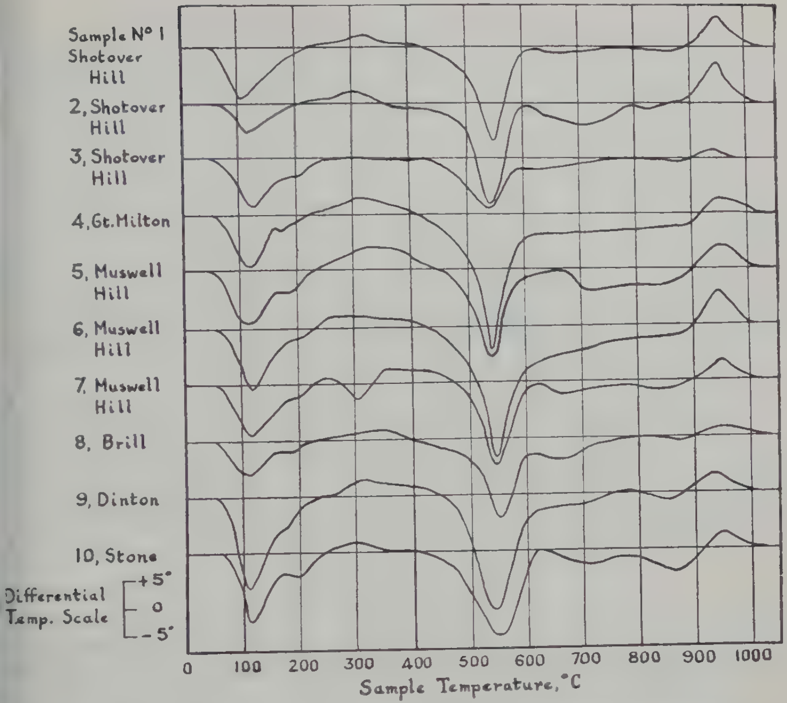

Fig. 2. Differential thermal curves of clays of the Shotover Ironsands

instance were made by a semi-micro method, using normal ammonium acetate solution adjusted to pH 7.0 in order to substitute ammonium ions for the replaceable cations originally present in the clay. The ammonium in the clay was determined by the Kjeldahl method after washing with 95% neutral alcohol to remove the excess ammonium acetate.

Duplicate analyses showed agreement to within a few milli-equivalents. Average values for nine samples from the Shotover series are as follows:

Locality	Sample Number	B.E.C. (me/100 gm.)
Shotover Hill	1	17
Shotover Hill	2	16
Shotover Hill	3	20
Great Milton	4	16
Muswell Hill	5	19
Muswell Hill	6	24
Brill Hill	8	8
Dinton	9	30
Stone	10	25

Most of these values are in accordance with those quoted for fireclays and other transported kaolins composed chiefly of the fireclay mineral. The values for samples Nos. 3, 6, 9 and 10 are higher than most published figures relating to fireclays. Comparing the base exchange capacities with the differential thermal curves it will be seen that the higher B.E.C. figures occur in those samples which show a rather large endothermic peak in the 100° to 200° C. region, and the coincidence of these features suggests the presence of illite in these samples.

Two samples (No. 8 from Brill, and 5 from Muswell Hill) were submitted to a commercial laboratory for powder X-ray analyses. Both were reported to give patterns suggesting the fireclay mineral and an abundance of quartz. In neither could montmorillonite be detected, nor was illite present in these particular cases.

The combined evidence therefore points to the fireclay mineral of Brindley & Robinson as the predominant clay mineral in the clays of the Shotover Ironsand series, with illite as a probable occasional additional component. Some of the illitic clays may have been sufficiently active to have been used in the past for fullering, and this may have led to the reports of the presence of fuller's earth.

4. HEAVY MINERALS

The heavy minerals of sixteen Shotover Ironsand samples were separated by centrifuging in tetra-bromo-ethane. The heavy residues represent about 0.2% by weight of the sand samples. The same varieties are present in samples from all the separate outliers and throughout the vertical range of the Shotover Ironsands, and although the relative abundance of the individual species varies, the variation between closely located samples is as great as that between different outliers and different levels.

Only five species of non-opaque heavy minerals occur with a regular relative abundance of more than 1% by number. They are the stable minerals zircon, tourmaline, rutile, kyanite and staurolite. They are accompanied by small but persistent amounts of sillimanite, garnet and anatase. Rare grains of corundum, chloritoid and enstatite were noted.

Drawings of the commonest minerals are provided (Figs. 3, 4 and 5) to show the degrees of abrasion and the varieties of shape present. In order to represent all the types present the drawings tend to exaggerate the importance of some of the rarer forms. Thus although six near-euhedral varieties of zircon are shown, all of these are in fact quite scarce.

The characteristics of the various minerals are described below:

(a) Zircon

This is by far the most abundant mineral, making up about 45% of the non-opaque heavy residue, and represented by a wide range of varieties.

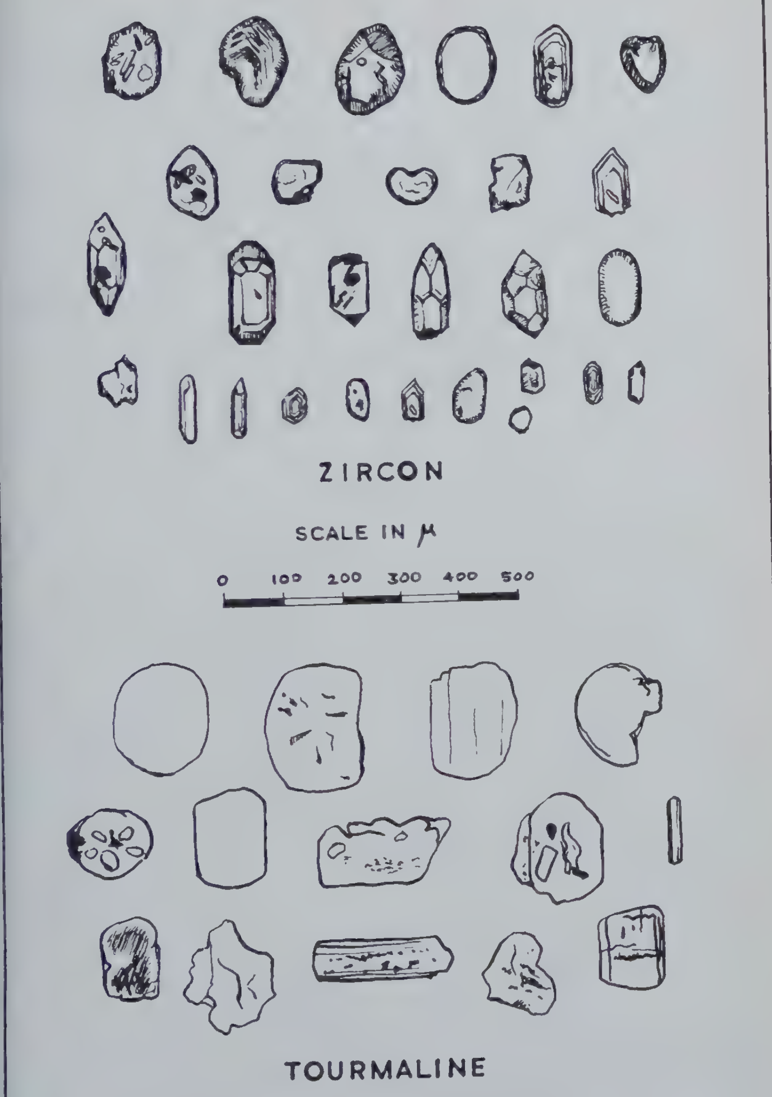

Fig. 3. Drawings of typical grains of zircon and tourmaline from the Shotover Ironsands

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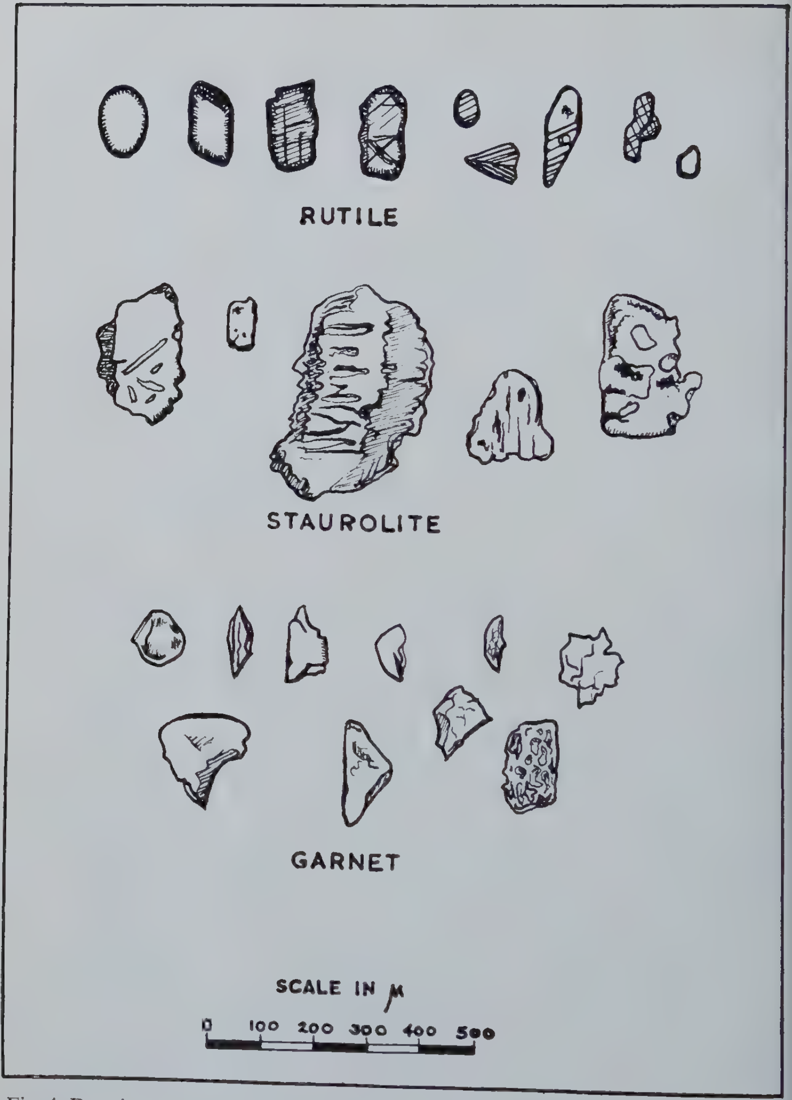

Fig. 4. Drawings of typical grains of rutile, staurolite and garnet from the Shotover Ironsands

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Sizes range from 20 microns to 200 microns, with an average of about 80 microns measured across the *b* axis. The commonest type is the moderately rounded grain still showing slight evidence of the original prismatic shape. It is clear and colourless, with relatively few inclusions. Zoned varieties also occur, usually displaying better crystal shape. Perfectly rounded grains and near-euhedral types can be found over the whole size range, but the rounded grains are commonest in the largest sizes, while the more euhedral varieties, though never common, are more often seen in the smaller sizes.

A few rose-coloured grains, invariably well rounded, occur in most samples and become common in samples containing the coarser grades. Yellowish rounded grains also occur occasionally.

Of the forms displaying some crystal shape, the commonest is that combining the second order pyramid with the second order prism. The other common combination is that of first and second order prisms with first and second order pyramids, giving rise to rather pointed crystals.

(b) Tourmaline

Tourmaline is the next most abundant mineral and forms about 22% of the non-opaque suite. The size ranges from 20 to 380 microns with an average of about 120 microns. Again great variety of shape and colour is shown by this mineral, as is usual in British sediments. Well-rounded grains, irregular flakes and typical laths with rounded pyramidal terminations occur in roughly equal proportions. Absorption is very strong in some varieties, pleochroism being from nearly opaque to nearly colourless. The following colours were noted, roughly in order of abundance: olive green and browny greens; various smoky greens and browns; purplish brown; yellow-brown; blue; and occasionally parti-coloured, green and pink. Dark inclusions and cavities are very common. A few prismatic grains have ragged terminations suggestive of solution, and a very few have a decidedly corroded appearance, with almost as much cavity as crystal.

(c) Rutile

This mineral has an average relative frequency of some 15% and varies in size from 20 to 190 microns, with an average size of 85 microns across the *b* axis. Foxy red abraded grains are commonest, closely followed by golden-coloured varieties. Grains showing good crystal shape are seen among all the sizes and colours present. The characteristic striations parallel to the principal and (101) crystal axes are commonly seen in grains of whatever colour or shape, although less so in extremely abraded forms. Very occasional arrow-head twins of golden colour are present.

(d) Kyanite

Kyanite is a prominent mineral in the heavy residues from the Shotover Ironsands, occurring to the extent of about 10%. In character it is of the type commonly thought of as typical of the Lower Greensand in this country, occurring in flakes and laths often up to 380 microns across. It is colourless and fresh-looking with rather sharp edges and angular outlines due to the characteristic cleavage. Carbonaceous inclusions are common. A few very cloudy and more rounded grains are also seen.

(e) Staurolite

The staurolite, forming roughly 8% of the non-opaque minerals, is of typical golden-brown colour with slight pleochroism, and exhibits the 'hackly' outline and 'Dutch cheese' appearance so characteristic of this mineral as a result of solution. Sizes range from 30 to 380 microns, with an average of about 130 microns across the intermediate axis.

(f) Sillimanite

A few grains of this mineral are found in most of the samples studied, and it occasionally occurs to the extent of 2%. It occurs as elongated laths with ragged terminations, colourless, but often cloudy with dark inclusions. The crystals are frequently curved.

(g) Garnet

Garnet is not always seen in the heavy residues of Shotover material and seldom reaches more than 0.5% of the non-opaques. Occasionally over 1% is found, and in one sample (No. 21) from Brill, 8% was recorded. It is present in the form of small, often crescentic chips showing conchoidal fracture and slight etching. These characters are said by Sindowski (1949) to be the effect of solution on this mineral, and solution may well be responsible for the uneven distribution of the garnet.

(h) Anatase

Some very small, golden, striated tablets of anatase are present. They are usually in clusters, often as outgrowths from fragments of opaque grains, and are evidently authigenic.

(i) Chloritoid

Occasional olive green or blue-green flakes somewhat resembling tourmaline, but with a higher refractive index, lower birefringence and pleochroism, and exhibiting a biaxial figure with well-marked dispersion were interpreted as chloritoid.

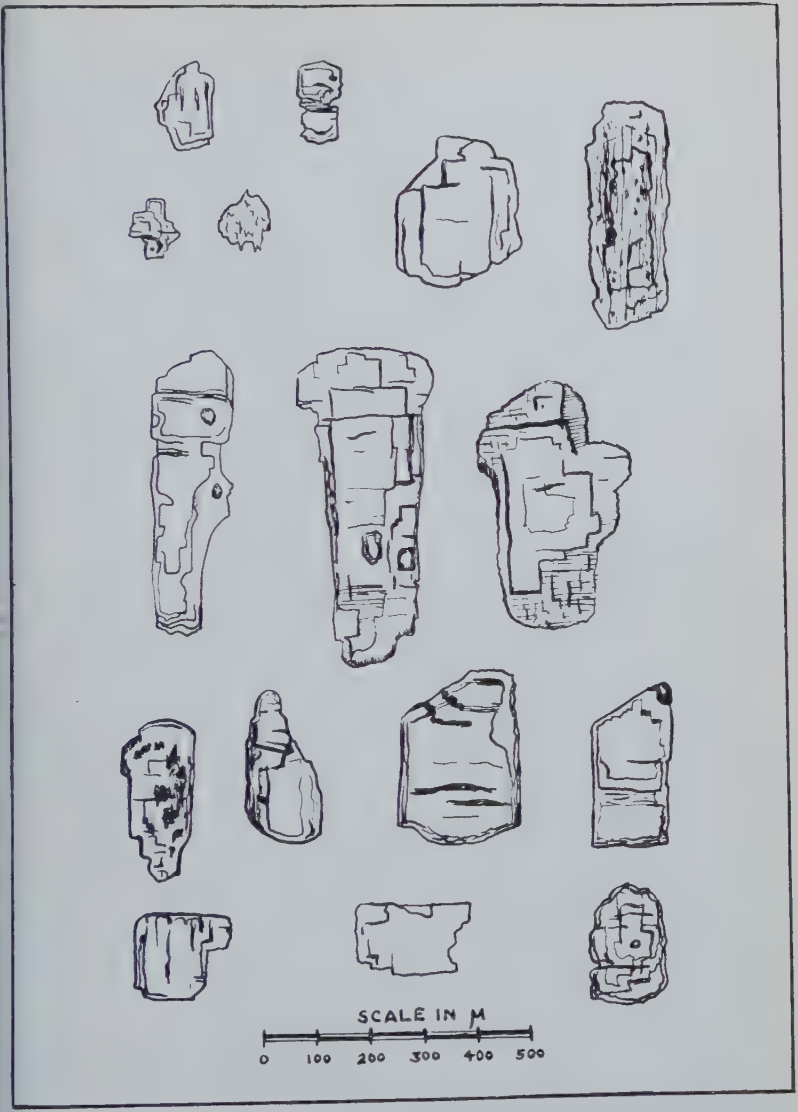

Fig. 5. Drawings of typical grains of kyanite from the Shotover Ironsands

[*To face p.* 248

(j) Corundum

Rarely, one or two grains of corundum, variety sapphire, are seen among the heavy minerals. They occur as small, sharp, angular fragments of beautiful clear pale blue colour, high refractive index and birefringence. These may, however, be adventitious.

(k) Enstatite

Very rarely a grain of a member of the pyroxene family is observed, having the optical properties of enstatite.

(l) Opaque Minerals

About 50% of the total heavy mineral residue of the Shotover Ironsand samples consists of opaque grains. Most of these are externally brown or white, and polished sections of mounts of some of these grains showed that the brown and white material continues right to the centre in nearly every case. The material is probably limonite and leucoxene, presumably representing the alteration of original grains of hematite, magnetite or ilmenite. A few unaltered magnetite grains were observed.

Some compound quartz-opaque grains and fine aggregates of indeterminable material also occur.

Provenance of the Heavy Minerals

A study of the literature concerning the heavy minerals of British sediments suggests that the varieties of zircon, tourmaline and rutile found in the Shotover Ironsands are in no way unique, and could have been derived, for instance, from almost any of the Palaeozoic and Mesozoic sediments of the English Midlands. The generally worn appearance of most grains of these minerals in the Shotover Ironsands is in accord with the notion of derivation from earlier sediments.

The presence of the metamorphic minerals staurolite, kyanite and sillimanite might at first appear to suggest a more exotic source of supply. Similar varieties of kyanite and staurolite, however, have been described by Neaverson (1925) from the Upper Kimeridge and Portland Sands of Dorset, Wiltshire, Oxfordshire and Buckinghamshire. Not only the staurolite and kyanite, but the whole suite described by Neaverson is strikingly similar to that found in the Shotover Ironsands, both as regards varieties and abundance. The only mineral listed as common in the Kimeridge and Portland but rare in the Shotover series is garnet. Garnet is known to suffer solution fairly rapidly, particularly under acid conditions, so that a reduction in abundance would be expected with each cycle of erosion and deposition, provided no fresh primary material were available. Samples of Portland Sand from Shotover Hill examined by the present writer yielded a heavy mineral suite which was virtually indistinguishable from that of the Shotover Ironsands. The fresh appearance of the kyanite does not necessarily contradict this suggestion that the mineral is reworked from earlier sediments for, unlike garnet, kyanite is resistant to chemical weathering, but tends to break up mechanically during transport. Consequently transport over moderate distances, by breaking off fragments along the cleavage planes, tends to increase the fresh appearance of kyanite while not unduly reducing the size of the grains.

The extensive literature which exists on the heavy minerals of the Wealden of south-east England and Dorset was examined for any similarity with the Shotover Ironsand suite. Zircon, tourmaline, rutile and opaque minerals are widespread and common. Staurolite is fairly frequently mentioned, but kyanite and sillimanite are very rare. The small spired staurolite and kyanite grains from the Ashdown sand figured by Allen (1948) are quite different from the varieties seen in the Shotover beds. In only two instances is mention made of significant amounts of kyanite in the Weald; it is noted by Milner (1925) from the Ashdown sand near Eastbourne and Hastings, and by Fitch (1930) from the Ashdown sand of Robertsbridge and Etchingham. In the latter case, however, staurolite was absent. According to Groves (1931) fresh kyanite and staurolite occur in the Weald Clay of the Isle of Wight and have probably been derived from Brittany, while the kyanite which is present in the Lower Wealden of Dorset has evidently been reworked from the Jurassic rocks.

All these other recorded occurrences of staurolite or kyanite are from rather far afield. Some core samples from the Wealden series in the Kingsclere boring (which is about thirty miles SSW. of the area in which the Shotover Ironsands outcrop, and the closest proved occurrence of other Wealden beds, so far as the writer is aware) were available to the writer through the courtesy of the Geological Survey Museum. Most of the samples were of very fine grained material with a predominance of clay and silt. Samples from two of the sandiest portions of the cores were taken for heavy mineral separation, one from —675 feet and one from —658 feet. The heavy minerals were very similar in the two samples, the composition being noticeably different from that of the Shotover Ironsands, being as follows:

Opaque minerals	45% of the total heavy residue
Tourmaline (blue-green and brown-green)	65% of the non-opaque heavy minerals
Zircon	21% of the non-opaque heavy minerals
Rutile	13% of the non-opaque heavy minerals

Staurolite and kyanite were both present to less than 1%, and all other minerals together formed less than 1% of the non-opaque heavy minerals.

SUMMARY AND CONCLUSIONS

The similarity of the heavy mineral suites of the Shotover Ironsands and the Upper Kimeridge and Portland Sands suggests that the material forming the Shotover beds was locally derived. Further support is given to this suggestion by the occasional occurrence in the Shotover sands of heavily limonitised glauconite grains, and in the coarser sands of abundant rounded and polished fragments of chert, for glauconite is very abundant in the underlying Portland beds, and the base of the Portland series is marked by a concentration of chert ('lydite') pebbles. There are no rock fragments in the Shotover Ironsands suggesting derivation from outcrops of an igneous or metamorphic nature, and felspar is a rare constituent.

Upper Jurassic strata would presumably have been available for reworking on the flanks of the uplifted London Island near at hand, from the close of the Jurassic period until the marine transgression of the Gault.

If, as is generally agreed, the Shotover Ironsands are of Wealden age, the difference between their heavy minerals and those of the Wealden of the northern rim of the Weald, and even those of the Kingsclere region, would seem to indicate that no important exchange of material took place between the two areas. Some connection with the Wealden of Dorset is possible, though in view of the distribution of Upper Jurassic rocks, it is not necessary to postulate such a connection in order to account for the similar mineral assemblages.

The presence of the Lower Greensand and Gault limits the surface evidence concerning the southerly extent of the Shotover Ironsands. The writer searched all available records of wells and borings covering a considerable area south of Oxford published by the Geological Survey. In all cases, where the wells are deep enough, Lower Greensand is reported to rest directly on Kimeridge Clay or on lower beds of the Jurassic. Occasional descriptions of the nature of the 'Lower Greensand' did not suggest that the material might have been misinterpreted Shotover Ironsands. If originally present at all south of the present outcrops, therefore, the Shotover Ironsands must have been planed off before or during the Upper Aptian or Lower Albian transgression.

The clays of the Shotover Ironsands are typical fireclays. Many clay mineralogists incline towards the view that the formation of particular clay minerals is governed more by the conditions during the weathering of the parent rock, and at and shortly after the time of deposition, than by the nature of the parent rock itself. In particular it is thought that kaolinitic clays are readily formed from other types by the leaching action of acid waters in a swamp environment (see, for instance, Ross & Kerr, 1931, and Millot, 1949 and 1951). Such aggressive conditions would also be likely to lead to the formation of the clean white sands and silts which are such a feature of the Shotover Ironsands, while locally active plant growth, by subtracting from the water carbon dioxide and liberating oxygen, would produce the less acid and more oxidising conditions favourable for the precipitation of the iron of the ferruginous beds.

Thus the nature of the common clay mineral, the absence of calcareous strata or calcareous micro-fauna in the clays, the presence of the plant remains noted by earlier field workers, and the local concentration of oxides of iron all agree with the accepted opinion that the Shotover Ironsands were formed under swampy fresh water conditions.

ACKNOWLEDGMENTS

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The writer wishes to thank Professor V. C. Illing, Dr. G. D. Hobson and Mr. S. E. Coomber for their guidance and encouragement, and the staff of H.M. Geological Survey for information concerning the Kingsclere boring. His thanks are also due to Mr. L. R. Barrett and Dr. G. M. Gad, of the Ceramics section of the Department of Applied Chemistry of Imperial College, for the loan of their Differential Thermal Analysis apparatus and for valuable advice on the technique of operation and the interpretation of results, and to Dr. B. S. Neumann of the Fuller's Earth Union, Nutfield, Surrey, for her advice on a procedure for Base Exchange Capacity determinations suited to the sticky impermeable nature of the Shotover Clays.

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APPENDIX

TABLE I: **Table giving localities: of clay samples examined by D.T.A. and Base Exchange Capacity methods, and sand samples of which the heavy minerals were studied:**

Sample number	Material	Locality	Six figure Grid Reference*
1	Clay, cream	Shotover Hill	564061
2	Clay, white	Horspath Common	571056
3	Clay, white	Shotover Hill	572055
4	Clay, grey, silty	Great Milton	641026
5	Clay, white	Muswell Hill	640152
6	Clay, white	Muswell Hill	647149
7	Ochre	Muswell Hill	647149
8	Clay, white, silty	Brill	657142
9	Clay, pale grey	Dinton	761112
10	Clay, white	Stone	780126
11	Sand, pale yellow	Shotover Hill	565062
12	Sand, yellow	Shotover Hill	572052
13	Sand, grey	Shotover Hill	575058
14	Sand, ferruginous	Wheatley	589052
15	Sand, clayey, pale grey	Wheatley	589052
16	Sand, ferruginous	Muswell Hill	642151
17	Sandrock, ferruginous	Muswell Hill	647148
18	Sand, orange	Muswell Hill	647149
19	Sand, pale yellow	Brill	657142
20	Sand, buff	Brill	657142
21	Sand, clayey, ferruginous	Brill	658132
22	Sand, yellow	Stone	780126
23	Sand, white	Stone	780126
24	Sand, white, with chert pebbles	Stone	780126
25	Sand, white	Stone	780126
26	Sand, clayey, cream	between Dinton and Haddenham	750108

* All Grid References lie within the 100 km. square 42/.

Field Meeting in the Central Inlier of Jamaica

JAMAICA GROUP

24 November 1957

Report by the Director: J. B. WILLIAMS

TWENTY-ONE MEMBERS and friends assembled in Kingston and drove in six cars to Christiana, a distance of nearly seventy miles, where they met the Director. The party proceeded through Spaldings and White Shop to the road that follows the Rio Minho eastwards into the Cretaceous inlier. While still on the Yellow Limestone (Eocene) Shales, a stop was made to explain the panoramic view of the inlier, the northern flank of which is particularly well seen from this part of the periphery.

The Central Inlier is a composite anticline with an E.–W. trend. Main Ridge, which was seen towards the south-east, constitutes the core of the principal upfold. Several faults trend in the same general direction, and these structural elements determine the course of the Rio Minho. The down-dip migration of this river has resulted in the opening up of a broad valley in the tuffs and conglomerates, overlooked by the horst-like mass of Main Ridge to the south. The view north-eastwards towards the 'feather edge' of the Tertiary Limestones, with 'cockpit' silhouette on the skyline, provides a graphic demonstration of the immense amount of material which has been removed from this enormous valley inlier.

The opportunity was also taken at this point to augment the geomorphological grandeur of the scene with an explanation of the succession (see map, Fig. 1).

The flanks of the anticline are covered unconformably by the Tertiary Yellow and White Limestone Formations, the dips being steepest on the south side. On this flank the predominant faults trend NW.–SE., the same direction as the Yallahs–Wagwater tectonic belt and the Blue Mountain ridge.

The formations described by Sawkins (1869) as the Trappean and Metamorphic Series have been identified as Upper Cretaceous, and are now subdivided as follows:

Upper Tuffaceous Series	Tuffs, tuffaceous sandstones and conglomerates.
Rudist Limestone Series	Nodular and massive limestones intercalated with and grading into calcareous shales.
Lower Tuffaceous Series	Red weathering argillaceous beds and loose conglomerates.

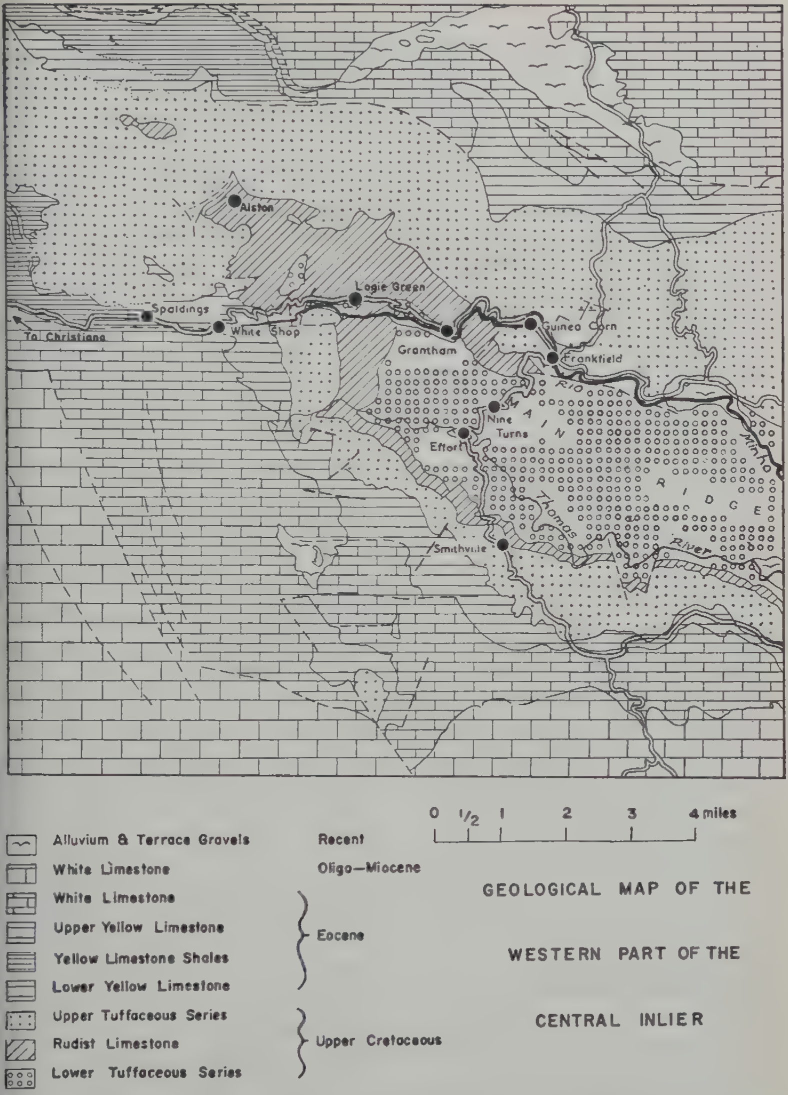

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Fig. 1

	Unconformity
Lower Rudist Limestone	Nodular limestone with Rudists.
Inoceramus Shales	Brown tuffaceous and calcareous shales with molluscan fauna.
Basal Conglomerate	Pebbles of igneous rocks in a tuffaceous matrix.

The whole succession, especially in the eastern part of the Central Inlier, is intruded by dykes and extensive masses of andesitic and granodioritic rocks, the latter being the latest intrusions. Some of these are associated with small-scale copper mineralisation.

The basal conglomerate, consisting of pebbles of andesitic and basaltic rocks, is overlain by a thick series of tuffaceous shales with *Inoceramus*, which occur only in two areas of the inlier, namely, on the southern slope of Juan de Bolas and in the Arthur's Seat district. This series which is associated with the Lower Rudist Limestone is here much disturbed and cut up by faults.

The Lower Tuffaceous Series, which overlies these beds unconformably, consists of a conglomerate series markedly coarser towards the base. The estimated minimum thickness is about 2500 feet. The beds are totally devoid of organic remains and comprise pebbles and boulders of basic and intermediate igneous rocks in a matrix of tuffaceous material and rock detritus. In several localities, notably at Effort Bridge, these beds have been intruded and metamorphosed by minor basic intrusions, resulting in some cases in the conversion of the sedimentary beds into dense grey hornfels, closely resembling normal volcanic rocks.

At the base of the Upper Rudist Limestone, conformable to the conglomerates and overlying them, is a shale horizon about 500 feet in thickness. The lowest beds consist of unfossiliferous red-weathering clay-shale overlain by fine laminated clay-shales which contain a fauna of small molluscs together with plant remains, and show traces of ripple marking. Above the shales is the Rudist Limestone, a formation widely exposed north of the Rio Minho between Guinea Corn and Alston, and more narrowly on the southern side of the Inlier. On the northern side, east of Frankfield, the limestone splits into very thin beds separated by a considerable thickness of shaly, sandy and calcareous material with some clay and lignitic intercalations with plant remains. The thickness of the main limestone horizon is somewhat variable but averages 250 feet in the western outcrops. The lower part is massive and blue-hearted and yields *Praebarrettia* and *Durania nicholasi*; the upper division is characterised by the presence of *Titanosarcolites* and many other Rudists.

The Upper Tuffaceous Series outcrops in a zone marginal to the Rudist Limestone, rather narrowly to the south, but occupying a wide area on the western and northern sides of the Inlier. It rests unconformably on various horizons of the underlying beds, and consists of two lithological types, whose relative stratigraphic position is, however, uniform.

The basal division is a thick series of conglomerates which in places become extremely coarse. In a matrix which is predominantly tuffaceous are well-rounded boulders and pebbles of several types of volcanic rock; porphyritic andesitic is the type most commonly encountered. The characteristics of this formation suggest that it is the result of rapid erosion and deposition in a tectonically unstable environment. The upper part of the series is tuffaceous, extremely homogeneous with few pebbles or boulders, and is of greyish-purple colour, weathering red at high levels.

From the vantage point below White Shop, the party proceeded eastwards. The first formation encountered beyond the Tertiary boundary was the Rudist Limestone, which is well exposed in road sections along the road to Grantham; several sections were examined, in particular that of the type locality at Logie Green, and a number of rudistids were collected. Below the limestone sporadic exposures of the finely laminated red shale of the Lower Series were seen which are repeated along the road by a number of small faults. Passing through Grantham, which is on a terrace of the Rio Minho, the traverse continued through Guinea Corn, where the steeply dipping Rudist Limestone of the northern limb of the anticline is well exposed in the incised meanders of the Rio Minho. The convolutions of the river in this area conveniently expose the junction between the limestone and the overlying tuffs, and the party spent some time here examining various sections, after which a picnic lunch was taken by the riverside.

After lunch the grey tuffs and conglomerates of the Upper Tuffaceous Series were examined at various places along the road to Frankfield, where the road going southward over Main Ridge was taken. Between here and the top of the hill at Nine Turns road-cuttings provide an almost continuous section of the Upper and Lower Tuffaceous Series and the intervening Rudist Limestone. Nine Turns is situated at the western end of Main Ridge, a typical hogback rising to 2700 feet, formed of the tuffs and conglomerates of the Lower Tuffaceous Series. This folded mass of waterlaid pyroclastic material is penetrated at several points by zones of invasive metamorphism, associated with basic and intermediate dykes and sills, which have had the effect of reinforcing the ridge against erosion and assuring its topographical dominance of the inlier.

The best exposures of sediments altered in this way can be seen in the bed of the Thomas River, at Effort Bridge, and accordingly a lengthy stop was made here to examine the compact greyish hornfels with its strings of 'ghost' pebbles, extensively penetrated by dykes and sills of intermediate basic composition. Southwards from the river roadside sections show a gradual diminution of metamorphic effect, and half a mile north of Smithville the conglomerates are entirely unaltered. Immediately north of that village a stop was made to demonstrate the very good section in the shales underlying the Rudist Limestone, provided by the bed of a small stream, which conveniently exposes extensive ripple marking, and in the thin overlying grey shales a proliferation of small molluscs.

After examining this section, the party returned to Kingston independently.

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Field Meeting at Dallas and Cane River Falls, Jamaica

JAMAICA GROUP

28 September 1958

Report by the Director: V. A. ZANS

THE MAIN OBJECT of this Field Meeting was to investigate some of the lesser-known gypsum deposits in the vicinity of Dallas, and to visit the picturesque Cane River Falls, where the river plunges into a deep gorge cut through the White Limestone of Dallas Mountain.

From Kingston the party, consisting of twenty members and friends, drove to Papine and Mona, taking thence the Dallas road, which crosses the Hope River at the ford below the University campus, winds up the western slope and then skirts the northern end of Dallas Mountain which is composed of the White Limestone Formation. The first stop was made here and the White Limestone was examined in road-cuttings. While on the western slope of the mountain the younger (Miocene) beds of this formation are seen; at this point upper Eocene rocks are exposed with *Dictyoconus* and occasional *Lepidocyclina*. The hard, greyish, recrystallised limestone is here strongly shattered and in places dolomitic. Underlying it, in the gully below the road, outcrop soft brown Eocene shales and clays (the White Limestone Basement Series of Matley). Across the gully to the north the old Hope Mine could be seen, where veins of lead and zinc sulphides, occurring in the Wagwater Conglomerate Series, were mined a hundred years ago.

The next stop was at Lindos Gap where deeply weathered and shattered andesitic rocks and conglomerates of the Wagwater Series were examined. These outcrop along the eastern side of the Wagwater Thrust, which runs at the foot of the eastern slope of Dallas Mountain. This major fault originated during the late Laramide diastrophic phase, when the Wagwater Conglomerate and shaly-sandy beds of Lower Eocene age were folded and pushed towards the south-west so that they now abut granodiorite and other Cretaceous rocks. The road follows the line of the fault which is generally concealed but was seen in a road-cutting about a mile south of Lindos Gap.

The party then proceeded to Dallas and examined several gypsum deposits. These occur along the thrust zone, trending NW.–SE., and are associated with the Wagwater Conglomerates and Lower Eocene Shales. The largest deposit in the area is that to the north of the Dallas post office and forms a hogback between two side gullies of the Barbecue River (an upper reach of the Cane River). It has been recently surveyed by the Geological Survey and appears to be of considerable size, but exploratory drilling is necessary to ascertain its full extent below the surface. The gypsum is of high quality, comparable to that at present exploited at Brooks and Beito, north of Bull Bay. The length of the gypsum exposure is 580 feet, the width being 175–180 feet. The deposit appears to be a diapiric body protruding through and along the junction of the Wagwater Conglomerates and the Lower Eocene shales; it is possible that this deposit extends to a considerable depth, and might be of economic value. Similar deposits of gypsum occur at Friendship Brook, about a mile and a half farther to the south-east.

The party then returned to Dallas road and proceeded to Cane River Falls, where lunch was taken. After lunch members walked down into the canyon below the falls. Cane River Falls and canyon provide an interesting example of river capture. Cane River, after joining Mammee River, formerly flowed away to the south-east along the line of the Wagwater Fault reaching the sea at Bull Bay. On this route the river carved its valley in soft Eocene shales. However, the open joints and fissures of the hard White Limestone forming Dallas Mountain offered at a later stage a shorter and steeper route to the sea. At first this took the form of an underground tunnel developed along the transverse joints. In flood periods, part of the Cane River flow was diverted into this tunnel overflowing into sink-holes in the Eocene Limestone. The subterranean passage was enlarged more and more by solution and erosion, until finally all the water took this route. Collapse of the roof of the tunnel followed and at present the river below the falls can be seen flowing through a narrow steep-sided canyon cut right through Dallas Mountain. The cliffs of the gorge attain in places a height of about 1000 feet and large fallen blocks remain as evidence of the roof collapse. The lower section of the old valley between Newstead and Bull Bay was deserted by the river, and today is mostly dry or occupied by a small 'misfit' stream, which gets swollen only after heavy rains.

The last stop was at a limestone quarry close to the road, about a mile north of Bull Bay, where the highly fossiliferous basal beds of the White Limestone (Middle Eocene) are well exposed. Specimens of fossils were collected including among the Foraminifera *Fabiania cubensis*, *Dictyoconus americanus*, *Lepidocyclina antillea*, *Discocyclina* spp. and *Fabularia matleyi* in addition to some poorly preserved pelecypods and gastropods. From a point near the quarry a fine view was obtained over the abandoned lower portion of the Cane River Valley, coinciding with the Wagwater Fault. Sugar Loaf Hill at Bull Bay with its vertical coastal cliff, probably a fault scarp, was also observed and photographed from the same point.

The party then proceeded to Bull Bay and returned to Kingston by the coastal road in the afternoon.

Field Meeting in the St. Ann's Great River Inlier, Jamaica

JAMAICA GROUP

25 January 1959

Report by the Director: L. J. CHUBB

ABOUT THIRTY MEMBERS AND FRIENDS took part in this excursion. The Kingston contingent assembled as usual at the Carib Theatre and drove some fifty-six miles to Lime Hall. They were joined *en route* by members from Lydford, Claremont and Golden Spring, and were met by the leader at Lime Hall, whence they drove down the winding track into the valley of St. Ann's Great River.

On the way down exposures of the Yellow Limestone Formation (Middle Eocene) were examined. Mr. Versey called attention to the dissimilarity between these structureless, fossiliferous limestones and the well-bedded, steeply dipping, chalky limestones seen on the main road above, between Lime Hall and St. Ann's Bay. The former are considered to be a mound-like accumulation of reef-derived calcareous detritus and the latter as deeper-water, bedded limestones, which flanked the mound on the north and west; their dip is thought to be original.

The parish of St. Ann, which occupies an area of over 500 square miles in the centre of the north coast of Jamaica, consists almost entirely of Tertiary limestones. St. Ann's Great River, however, which in Britain would rank as a small stream being little more than three miles long, has cut through these limestones to the underlying Cretaceous, forming a small valley inlier, half a mile wide, first mentioned by Sawkins (1869, 199). It has recently been surveyed by Zans (1954).

The first Cretaceous formation studied was the *Barrettia* Limestone which is well exposed both in the main river-bed and also in a tributary; it is only some twelve or fifteen feet thick. Many fossils were collected, chiefly rudists belonging to the genera *Biradiolites* and *Bournonia*, as well as *Plicatula* sp. and gastropods, including *Actaeonella* sp. and *Turritella* sp. The lowest ten feet of the overlying shales also yield rudists, some of them broken before burial, but from this horizon a complete *Barrettia* was obtained, some eight inches in diameter, the biggest ever found in this outcrop. A large meandroid coral was also collected.

The *Diozoptyxis* Shales, which overlie the *Barrettia* Series, were next examined. Many small molluscs belonging to the species described by Trechmann (1927) were found. These shales have yielded the foraminifera

Globotruncana fornicata, *G. stuarti* and *G. lapparenti*, proving that their age is Campanian, not Maestrichtian as suggested by Trechmann.

After lunch the conglomerates below the *Barrettia* Limestone were studied; their pebbles are chiefly igneous rocks, but a few are limestone. The road was followed northwards (downstream) but after a short distance it was found to be blocked by a fallen tree and the party had to proceed on foot. A track through the woods was taken to the river, and the *Inoceramus* Shales which underlie the conglomerate were examined by wading in the water. Several large specimens of *Inoceramus* sp. were found, but none of the small gastropods and lamellibranchs characteristic of this series. The foraminifera in this formation, including *Globotruncana coronata*, *G. helvetica*, *Gumbelina globulosa* and *Thalmanninella* sp., prove its age to be Turonian–Coniacian.

On the return journey the party was entertained with tea and other refreshments by Mr. and Mrs. C. S. Cotter, in their home at Golden Spring. Some members were privileged to see the wonderful collection of Arawak artifacts that Mr. Cotter had made in the course of his excavations at Seville and other sites in St. Ann.

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Easter Field Meeting in St. James and Trelawny, Jamaica

JAMAICA GROUP

7–12 April 1958

Report by the Directors: V. A. ZANS, L. J. CHUBB, H. R. VERSEY and E. ROBINSON

THIS WAS THE FIRST long excursion organised by the Jamaica Group. The object was to study the Cretaceous geology of St. James parish, and the Tertiary and Quaternary of St. James and Trelawny, as well as the Recent coral-reefs.

Sixth-form pupils from Clarendon College and Rusea's High School, where geology is now taught as an examination subject, were invited to attend, so that they might get some experience in field work. Fifteen took advantage of the offer, their expenses being largely met by a grant from the Ministry of Education, and vehicles to transport them being provided by the Geological Survey Department.

Including these students the total number of members and friends attending the meeting was thirty-eight. The headquarters were at Cornwall College, Montego Bay, where dormitory and other accommodation was kindly placed at the disposal of the Group by the Board of Governors. Here an inaugural meeting was held on the evening of Monday, 7 April, when a geological map of the area, prepared by the Geological Survey, was displayed, and the geological structure was explained by Dr. L. J. Chubb.

8–12 April

Mornings, Director: V. A. Zans

It is only in the early mornings that calm seas can be expected, in which navigation in a small boat among coral-reefs may be carried out safely. Accordingly, each morning at 6 a.m. a party of eight was driven from Cornwall College to Ironshore, six miles away, where a field-unit of the Geological Survey Department was camped.

The party was taken for a cruise in the departmental boat, specially built for the study of coral-reefs, of shallow draught, with two glass windows in its bottom, and equipped with compass, speedometer and echo-sounder. Members were piloted over the lagoon and reefs, and the geological features, the various zones of the reefs and the composition of the coral fauna were demonstrated. Diving to collect corals and other organisms was carried out by some members, and altogether twenty-five species of reef-building organisms were brought to the surface, including species of *Porites*, *Montastrea*, *Diploria*, *Acropora* and *Siderastrea*.

Members were landed for a time on the rampart of boulders which has been thrown up on the reef during storms, where they had an opportunity to collect specimens of corals as well as many other reef organisms, such as molluscs, echinoids and asteroids.

At 8 a.m. the coral-reef party returned to Montego Bay to join the other members for breakfast after which the main excursion of the day would start.

Tuesday, 8 April

Director: L. J. Chubb

The day was devoted chiefly to a study of the Sunderland Cretaceous Inlier. The party drove south-east from Montego Bay along the John's Hall road, passing over the Tertiary White Limestone Formation which here has the chalky Montpelier facies. Nearer Montego Bay the beds are horizontal but on approaching the Cretaceous inlier they were seen to dip at increasing angles until they became almost vertical.

The John's Hall Series, comprising the oldest Cretaceous rocks in the area, was seen in many road-cuttings around the village of the same name. It consists of volcanic conglomerates and tuffs, which were probably formed by submarine volcanic action, and were certainly laid down under water, as is proved by the occurrence of marine shells, such as *Nerinea* sp., in a stream section half a mile east of John's Hall. In some places the tuffs and conglomerates have been altered to a rock hardly distinguishable from andesitic lava by thermal metamorphism, due to the intrusion of numerous small dykes.

In many places in the John's Hall valley the tuffs and conglomerates are overlain by the brown shales of the Sunderland Series. This yields a foraminiferal fauna including *Globotruncana lapparenti lapparenti* Brotzen, *G. stuarti* (de Lapparent) and *G. fornicata* Plummer, which prove the age of the rocks to be Campanian. Near Sunderland these shales were seen to be dipping south at 40° off the John's Hall Series, which occupies the axis of an anticline. A large species of *Inoceramus* was observed on the bedding planes of these shales. The Sunderland Series continues south for a mile or more, generally dipping about 35° to the south, beyond which it is overlain by the grey Newman Hall Shales, which have the same dip. These contain the same species of *Globotruncana* as the Sunderland Shales, with the addition of *G. lapparenti tricarinata* (Quereau), indicating an Upper Campanian age (equivalent to the *quadrata* Zone of the English Chalk). Several small gastropods were found.

Immediately south of these shales the Stapleton Series was seen, still dipping south, at 45°. Its lowest unit is an eight-foot bed of light brown, decalcified clay-shale, showing impressions of lamellibranchs, echinoids and a large foraminifer which has been identified as *Meandropsina* sp. The overlying twenty-five foot *Barrettia* Limestone is one of the most famous formations in Jamaica, yielding *B. gigas* Chubb, and other rudists such as *Durania nicholasi* (Whitfield) and *Praeradiolites verseyi* Chubb, and foraminifera such as *Pseudorbitoides trechmanni* Douvillé.

Above the *Barrettia* Limestone there are eighty feet of shale containing small indeterminable fossils. This passes up by alternation into a nodular rudist limestone yielding, in its lower, more shaly, part a species of *Antillocaprina*, and in its upper, calcareous, part a primitive radiolite that is probably *Praeradiolites verseyi.*

Only the basal part of the overlying Shepherds Hall Series, a 2800-foot formation of volcanic conglomerates and tuffs, was seen. It is thought that this series forms the uppermost Campanian and that the overlying *Praebarrettia* Limestone, which is not actually exposed although its fossils are found in the soil on the slopes below Kensington, is basal Maestrichtian.

The party drove back to Sunderland, then east to Amity Hall, whence they circled round the east, south and west side of the Sunderland Inlier, the road approximately following the junction between the Cretaceous and Tertiary rocks. The *Barrettia* Limestone and the Shepherds Hall Series were seen again near Whitechapel Spring. Many fossils were collected from the Middle Eocene Yellow Limestone of Kensington, Welcome Hall and Spring Mount, including *Pauropygus ovumserpentinis* (Guppy), *Rhyncopygus matleyi* Hawkins, *Campanile giganteum* Lamarck, *Velates perversus* Gmelin, *Lucina* sp. and *Cardium* sp. It was noticed that everywhere the Middle Eocene Yellow Limestone rested directly with strong angular unconformity on different horizons of the Cretaceous. The Lower Eocene Richmond Beds or Carbonaceous Shale, so well developed in the Wagwater Belt east of Kingston, are here entirely lacking.

Wednesday, 9 April

Director: L. J. Chubb

The programme included a study of the Maldon Inlier of Cretaceous rocks, which lies about two miles south of the Sunderland Inlier. It is believed that the age of the rocks is Maestrichtian.

The party drove through Kensington and Point to Maldon where, in a road-cutting by the school and in the school yard, a limestone crowded with fossils, most of them rudists, was seen. Among the commonest species were *Titanosarcolites giganteus* (Whitfield), which commonly attains a total length of six feet, and *Thyrastylon adhaerens* (Whitfield), an important rock-building species.

Thence the route lay over the Popkin Series of red brown and purple shales and conglomerates, overlying the Maldon Limestone, as far as Maroon Town. Here the party turned south-west to Vaughansfield, where the highest Cretaceous limestone in this area was seen in the banana fields. Many fossils were found loose in the soil, including the two species mentioned above, as well as *Antillocaprina occidentalis* (Whitfield), *Bournonia cancellata* (Whitfield), *Chiapasella radiolitiformis* (Trechmann), *Goniopygus supremus* Hawkins, and numerous corals, the most abundant being *Dichocoenia trechmanni* Wells, *Multicolumnastrea cyathiformis* (Duncan) and *Dictuophyllia conferticostata* (Vaughan).

The last stop was at Shaw Castle where the Maldon Limestone was seen again with the same fossils as at the school. Here a road-section showed a shale, interbedded in the limestone, full of fossil shells, such as the rudists *Agriopleura falconi* Chubb, *Gyropleura shaviensis* Chubb and *Thyrastylon coryi* (Trechmann), as well as *Actaeonella* sp. and other gastropods.

Resting on the upper limestone the bright red shales of the basal Popkin Series were seen.

Thursday, 10 April

Director: H. R. Versey

This day was spent examining some of the hydrological features of the Queen of Spain's Valley, a polje a few miles east of the Sunderland Inlier. A stop was made on the hill north of Tilston where there is a good view across the valley to the Cockpit Country to the south. The White Limestone Formation of northern Trelawny is made up of two distinct facies, a chalk (the Montpelier member) and the normal type of the formation which consists of hard, crystalline limestones. These two facies are contemporaneous and the junction between their areas of deposition is furnished by one or other of the several faults of the east–west Duanvale Fault system, forming the northern edge of the Cockpit Country. It is to the relationship of these two facies that the development of the Queen of Spain's Valley is due. The ground water flowing from the catchment of the Cockpit Country, a karst area permeated with sink-holes and caves, developed in the crystalline facies of the White Limestone, is ponded up on reaching the Duanvale Fault system by the Montpelier chalks whose permeability is low. Many large springs issue along this line and flooding of the valley is frequently quite extensive. Lateral erosion and widening of the valley follows.

One such spring, draining the Maldon inlier, rises in Springvale, a smaller polje to the south, from a large but inaccessible cave. The resulting river flows for some distance, then after sinking reappears again from a series of caves at Deeside, at the southern edge of the Queen of Spain's Valley. These springs were visited and their relationship explained. At Windsor, another similar spring rises, close to the entrance of Windsor

Great Cave. This cave, probably over two miles in length, has been surveyed by the Geological Survey for three-quarters of a mile. During the field trip the party penetrated it for 200 yards, noting the various secondary limestone features and the accumulation of bat guano. The presence of only one Tilley lamp among a party of over twenty added to the interest of the excursion.

A visit was also paid to the site at which the diamond drill, operated by the Geological Survey, had just finished sinking a two and a half inch exploratory hole in connection with water supply. A tentative test of this well by pumping water at a rate of twelve gallons per minute for twenty minutes was made and no change of water level resulted. Since Easter this well had been reamed out to sixteen inches and on test gave 2000 gallons per minute with a drawdown of fifteen feet. This is the first, but not the last, successful well in the Queen of Spain's Valley.

Friday, 11 April

Director: E. Robinson

The day was devoted to an examination of the more recent rocks outcropping in St. James and Trelawny. A route was followed from Montego Bay towards Falmouth. The first stop was at the Airport Quarry, Montego Bay, which has recently been reopened. The quarry is in marly and rubbly white limestone belonging to the Upper Miocene Coastal Formations, subdivided in this region into The Hague Marl overlain by the Coralline Limestone. Several rather poorly preserved moulds of *Stylophora* and *Montastrea* were found, together with a few indeterminate molluscan remains. The Coastal Formations here have been planed off by wave action to form a terrace some twenty-five feet above sea-level. The quarry is in the front edge of this terrace.

A second stop was made near Rose Hall, to look at a thick bed of travertine of Recent age, containing numerous well-preserved leaf impressions. The party then drove on towards Falmouth and, after stopping twice on the road, first to look at a gravel fan and then at an Elevated Reef platform, reached Martha Brae and Hague Quarry. In Hague Quarry the Coastal Formations are developed as a pure white chalk. Although the party failed to find fossils except for a few fragments of algae, several very small impressions of molluscs and solitary corals have been found at other times.

After having lunched in Falmouth the party went on to Rock Quarry, a mile to the east, where there is a well-preserved fossil sea-cliff, with a wave-cut notch. This cliff, cut in the Coralline Limestone of the Coastal Formations, stands at the back of a fairly recent elevated reef terrace. The surface of this terrace was littered with molluscs and corals, the more common species including *Strombus* sp., *Bulla striata*, *Arca* sp., *Lucina* sp., *Montastrea annularis*, *M. cavernosa* and *Siderastrea* spp.

At the next stop, near Duncans, an interesting herring-bone pattern of fracturing was seen in unfossiliferous white marls. The last two stops were made near Braco. At the first an excellent section of the fossil sea-cliff and wave-notch was examined. The party then crossed the road and entered a small pit, dug as a water-hole. The ground-level here is only six feet above sea-level and the pit was excavated in the Falmouth Formation, a lagoonal facies corresponding to the Elevated Reefs which had been seen previously. In a soft cream marl innumerable mollusca are preserved in their entirety, similar in every way to species now living in the adjacent seas. *Melongena melongea* and *Bulla striata* were the most common fossils, but species of *Cerithium*, *Tellina* and *Chione* were also numerous.

On Friday evening a final meeting was held at Cornwall College. The work of the past week was reviewed, and a vote of thanks to the Board of Governors of the College and to Mr. E. A. Barrett, the Headmaster, for their hospitality, was passed unanimously.

Field Meeting at Bowden, Jamaica

JAMAICA GROUP

25 May 1958

Report by the Director: L. J. CHUBB

THE PURPOSE OF THIS MEETING was to study the Miocene rocks exposed along the coastal road which runs eastwards from Kingston to Bowden. Eighteen members and friends participated.

The first stop was at the Cane River Valley where the August Town Series, believed to be of Middle or Upper Miocene age, was examined. This series, which was first described by Matley (1940, 101; 1951, 39–40, 61–2), is best seen in the gorge of the neighbouring Hope River, where it consists of about 800–1000 feet of yellow sandy marls and limestones with, in its middle part, a thick breccia and conglomerate formation.

In the Cane River Valley the exposure nearest the road is in the breccia-conglomerate horizon and includes sandstones with worm-borings, and conglomerates with large rounded pebbles of far-travelled rocks derived from the Blue Mountains, and occasional massive corals, indicating the neighbourhood of coral-reefs. The dip is 35°–45° SSW. Higher upstream a lower horizon consisting of yellow sands and sandy limestones with steep or vertical dips was seen, but its relationship to the Eocene–Lower Miocene White Limestone, which outcrops a little beyond, is obscure.

Vertical August Town beds were seen again around a pond north of the road near the eighth mile-post. Here about 750 feet of soft calcareous sandstones were seen, intercalated at intervals of three or four feet with harder beds of sandy limestones some six inches to a foot thick. The strike is NW.–SE. Many fossils were found here, including species of *Pecten*, *Amusium*, *Spondylus*, *Lopha*, *Conus*, *Placocyathus*, *Montastrea* and *Stylophora*. The pea-like foraminifera, *Gypsina pilaris* (Brady), is everywhere in evidence. The zone of vertical August Town beds can be traced in a north-westerly direction from this spot for a distance of about three miles to a point in the Hope River gorge. It is no doubt connected with faulting and is parallel to the Wagwater Fault which is less than a mile away to the north-east.

The August Town Series was seen for the last time in a road-cutting near the ninth mile-post. It consists of the usual yellow sandy limestone, containing the ubiquitous *Gypsina pilaris* and *Placocyathus* spp. Beyond this point no rocks that could be ascribed to this Series were seen for many miles, all the roadside exposures showing the White Limestone Formation. On approaching Port Morant, however, at thirty-eight miles from Kingston, members examined the brown sandy and conglomeratic beds full of pebbles of volcanic rocks which form part of the Bowden Series. This Series is probably the same age as, or a little younger than, the August Town Series.

Driving round the head of Port Morant to its eastern side, the classical outcrop of the Bowden Beds was seen. From this locality came the collection of over 600 species of molluscs described by Woodring, as well as numerous corals and foraminifera. It is probably the most remarkable Miocene fauna that has been found anywhere in the world. All the fossils came from a lenticle of unconsolidated marl containing small pebbles and grains of volcanic rocks; it is only two or three feet thick and extends for a couple of hundred yards, at a height of about six feet above road-level. Unfortunately, owing to recent heavy rains, the exposures were found to be largely concealed by slipped soil and fallen trees, but a number of typical fossils were collected including *Gypsina pilaris* (Brady), *Placocyathus barretti* Duncan, *Thysanus excentricus* Duncan, *Arca* spp., *Echinochama antiquata* Dall, *Chama involuta* Guppy, *Pecten bowdenensis* Woodring, *Cardium haitense* G. B. Sowerby, 1*st*; *Chione hendersoni* Dall, *Strombus pugiloides* Guppy, *Oliva* sp., *Conus* spp. and other species. Above this fossiliferous bed the hill is composed of yellow earthy limestones and marls, containing moulds and impressions of fossils, which resemble those of the August Town Series.

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Field Meeting at Buff Bay and Low Layton, Jamaica

JAMAICA GROUP

27 July 1958

Report by the Director: E. ROBINSON

THE PARTY OF TWELVE MEMBERS assembled outside the Carib Theatre, Kingston, and during the drive to the north coast two additional car-loads of members and friends joined the group at Annotto Bay.

The first stop, about a quarter of a mile east of Buff Bay, was made to examine a well-exposed roadside section of the Coastal Formations. An alternating series of brown clays and yellow, rubbly and partly indurated coral limestones dips gently north-west at this point. The limestones contain numerous but poorly preserved fossils, many in a rather broken state. Corals seen included *Dichocoenia tuberosa*, *Montastrea annularis*, *M. cavernosa* and two or three species of *Stylophora*. Among the molluscs which were collected were specimens of *Plicatula*, *Ostrea*, *Turritella* and *Chlamys*. The interbedded clays are particularly rich in small foraminifera. Over 250 species have been reported from this locality. Only the larger forms, such as *Robulus* and *Amphistegina*, were seen with the aid of a lens.

This alternating series of clays and limestones passes down into grey and brown calcareous clays containing many foraminifera and occasional moulds of molluscs. These beds in turn rest on a chalky white limestone, with a few flint bands, belonging to the White Limestone Formation.

The second stop of the excursion was at Hope Bay where lunch was consumed and members went bathing. After lunch the party inspected a superb cliff-section of pillow lavas belonging to the Low Layton volcanic series. The pillows, composed of vesicular lava, reached about three feet in diameter and often exceeded six feet in length. The internal structure of the pillows and the gradation from large vesicles at the centre to rock approaching pumice on the outside was well seen.

At one point in the cliff a volcanic neck is sectioned vertically and its distinctive pattern of radial and concentric joints was well seen. The lava in the neck was non-vesicular and cut cleanly across the vesicular lavas making up the rest of the cliff.

Owing to bad weather the excursion had to be terminated before the section showing interbedded limestones and lavas was reached. At this point the limestones are globigerinal and *Globigerina* sp. can often be found, in a lime matrix, in the vesicles of the lavas. Although the age of these limestones is not known, clays, limestones and conglomerates of the Coastal Formations overlie the volcanic rocks, and the globigerinal limestones may correspond to the top part of the White Limestone Formation, perhaps Lower or Middle Miocene.

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Palaeocurrents and Sedimentary Facies of the Dalradian Metasediments of the Craignish–Kilmelfort District

by JOHN L. KNILL

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ABSTRACT: The lithology and mode of deposition of a succession of Dalradian metasediments, now in a low-grade metamorphic condition, are described. The succession comprises three units:

Gleann Mor Limestone Group
Crinan Grits
Craignish Phyllites (with Shira Limestone).

Palaeocurrent observations show that the Craignish Phyllites and probably the Gleann Mor Limestone Group were derived from the NNW. and NW., in contrast to the Crinan Grits which flowed into the area from the NNE. The significance of these two distinct current directions is discussed.

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1. INTRODUCTION

THE CRAIGNISH–KILMELFORT district lies on the western seaboard of Mid-Argyll, some twelve miles south of Oban; the position of the area under discussion is shown in Fig. 1 (a). The country rocks consist of a sequence of Dalradian metasediments, now in a low-grade metamorphic condition. These rocks have been folded and dip in a general eastward direction underneath the Loch Awe Syncline (Bailey, 1913). The geology of the district is covered by Sheets 36 and 37 of the Geological Survey of Scotland and is described in the two accompanying sheet memoirs (Peach *et al.*, 1909, and Hill, 1905). Bailey (1913) reviewed the mapping of the Loch Awe Syncline and established the stratigraphical succession; this work was confirmed by Allison (1940) in the Kilmartin area, immediately east of the Craignish peninsula.

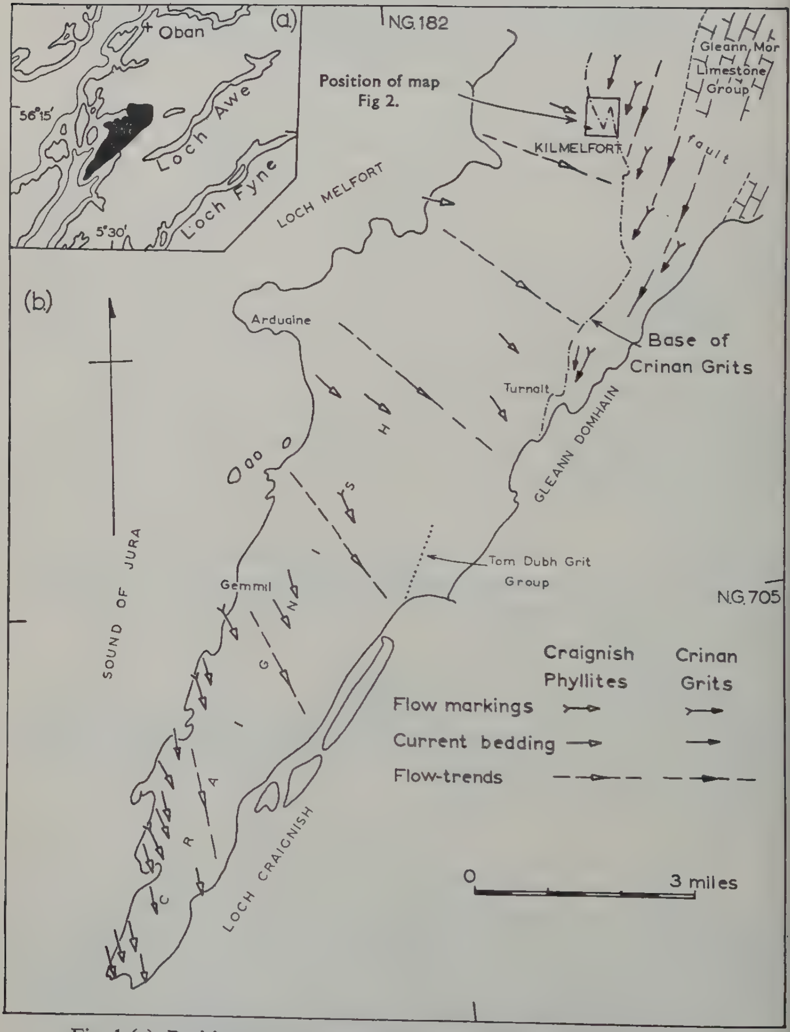

Fig. 1 (a). Position of the Craignish–Kilmelfort district, shown in black
(b). Palaeocurrent directions in the Dalradian metasediments

This paper is concerned with the description of a succession of sedimentary rocks which have been slightly metamorphosed during folding. Although the original textures and structures were, to a greater or lesser degree, deformed by the tectonic movements, it is still possible to study the conditions under which the sediments were deposited.

2. SUCCESSION

The succession of the Dalradian metasediments exposed in the Craignish–Kilmelfort district is as follows:

Gleann Mor Limestone Group	500 feet+
Crinan Grits	2000 to 2500 feet
Craignish Phyllites (with the Shira Limestone)	8000 feet+

The thickness of each stratigraphical group has been determined from the comparatively straightforward major structure, and is based upon the present condition of the metasediments. The total thickness of the Craignish Phyllites is considerably greater than 8000 feet, since the outcrop of this group continues westward well into the Sound of Jura. It may be noted that the thickness of Crinan Grits in the Craignish–Kilmelfort district is far greater than Allison's estimate of 200 feet in the Kilmartin area, on the eastern side of Loch Craignish (Allison, 1940, 431). Measurements of Allison's structural sections (1940, fig. 4, 437) suggest that the Crinan Grits in the Kilmartin area are nearer 2000 feet in thickness.

3. CRAIGNISH PHYLLITES

The Craignish Phyllites form the country rocks to most of the district, outcropping throughout the Craignish peninsula and along the margins to Loch Melfort (Fig. 1(b)). This group also extends southwards into the Sound of Jura and northwards crops out as inliers beneath the Old Red Sandstone Lorne Lavas. The Craignish Phyllites are generally believed to be equivalent to the Ardrishaig Phyllites of Knapdale, the Ben Lawers Schists of the Central Highlands (MacGregor, 1948) and the Port Ellen Phyllites of Islay.

The Craignish Phyllites are composed of an extremely mixed sequence of varied phyllites, quartzites, limestones and grits; lateral and vertical facies changes are rapid and frequent. A careful examination has been made of the relationship between the tectonic structure and 'way-up' criteria. This study suggests that the lithological variations are not the result of the tectonic repetition of a simpler succession, but represent original sedimentary differences. Consequently, there are few important stratigraphical horizons; one example is a zone of thin limestones which can be traced northwards up the western coast of Craignish from Gemmil to Loch Melfort, east of Arduaine.

The individual rock-types which comprise the Craignish Phyllites are described in turn:

(a) Phyllites

The phyllites are always fine-grained and marked by a strong slaty cleavage; sedimentary laminations are generally present. It is possible to divide the phyllites into several distinct groups, based upon their appearance in the field and their mineralogical composition. Most of the phyllites are composed of at least 50% quartz and this may be accompanied by varying proportions of calcite, chlorite, pale green muscovite, sericite and smaller amounts of epidote, pyrite, ilmenite, leucoxene and graphite.

Several different varieties of phyllites can be distinguished:

Quartz-phyllite
Quartz-sericite-phyllite
Muscovite- and sericite-phyllites
Calcareous phyllite
Quartz-chlorite-phyllite
Pyritic- and graphitic-phyllites

The quartz-phyllites are pale, thinly bedded rocks, composed of quartz and interstitial sericite and chlorite. The quartz-sericite-phyllites are more finely banded and darker in colour than the quartz-phyllites, owing to the presence of more abundant micaceous minerals. The muscovite- and sericite-phyllites are characterised by abundant white mica. They are generally closely associated with the calcareous phyllites which consist dominantly of calcite, with subsidiary quartz and muscovite. The quartz-chlorite-phyllites have a slate-grey colour and are composed of quartz, chlorite and a characteristic pale green muscovite. The pyritic- and graphitic-phyllites are found closely associated with the Shira Limestone in the upper part of the Craignish Phyllites. They are dark grey or black in colour owing to the presence of abundant finely disseminated pyrite and/or graphite associated with quartz and sericite.

These differing types of phyllite represent original sedimentary variations and may occur both interbedded with one another or as intercalations between the more competent horizons.

(b) Quartzites

The quartzites can be divided into two distinct groups: flaggy quartzites and massive quartzites.

The flaggy quartzites are laminated and occur intercalated with micaceous or quartzose phyllites; individual beds may vary from one inch to two feet in thickness. They have a general grain-size of 0.005 to 0.02 inch and are composed of recrystallised quartz, with abundant chlorite and muscovite.

Laminations may form individual graded beds from one to two inches in thickness. Some of the quartzite beds have a lenticular shape along the strike; the included graded beds thicken towards the centre of the lenticle. The terminations of the lenticle generally plunge down the dip of the bedding towards the ESE. or SE.; this plunge is paralleled by occasional flow-markings on the base of the quartzites. Sedimentary structures such as current-bedding and 'scour and fill' are frequent. Slumped beds and sedimentary breccias are also present.

The massive quartzites form distinct and, frequently, thick horizons within the succession, with individual beds varying in thickness from about one to four feet. Laminations, small graded beds, pebble beds, flow-markings and current-bedding are sometimes present. The quartzites are pale-coloured and composed of sub-rounded quartz grains, between 0.02 and 0.05 inch across, in a matrix of calcite with occasional flakes of muscovite and sericite.

Both varieties of quartzite frequently have a strong slaty cleavage and then closely resemble quartz-phyllites.

(c) Limestones

As a whole, limestones are not common in the Craignish Phyllites, apart from the upper part of the succession. The few limestones that occur form thin beds between one and six inches in thickness and are interbedded with micaceous phyllites; they are always composed of fine-grained calcite associated with subordinate quartz and mica.

(d) Grits

Grits are rare in the Craignish Phyllites except for some local, lenticular beds occurring just below the base of the Crinan Grits. A prominent NNE.–SSW. zone of grits can be traced for a mile from Hill Park through Tom Dubh to Loch Craignish (Fig. 1(b)). This group is about 150 feet thick and is composed of coarse-grained grits enclosing small fragments of micaceous phyllites. At the base of the group there is a sedimentary breccia, composed of small (0.25 to 1 inch) fragments of a fine-grained limestone.

(e) Shira Limestone

This group occurs in the upper part of the Craignish Phyllites where dark-coloured, graphitic- and pyritic-phyllites become more frequent, the general grain-size decreases and detrital debris is less abundant. Thick beds of dark grey limestone are intercalated with these dark phyllites; quartzites are infrequent. Three limestones outcrop on the hill north of Turnalt, but these disappear northwards; lenticular beds of contact-metamorphosed calc-silicates outcrop farther north and can be followed to the northern margin of the district. Immediately east of Kilmelfort there is a thick limestone with a basal breccia. This breccia is thought to be partly tectonic in origin and was formed by the disruption of an originally gritty limestone.

4. SEDIMENTARY ASSOCIATIONS WITHIN THE CRAIGNISH PHYLLITES

The variability of the Craignish Phyllites has been referred to above; detailed examination of the succession suggests that certain of the lithological types tend to occur together more frequently and thus form sedimentary associations. Four such associations may be identified:

(i) 'Clean-washed' association—massive quartzites; muscovite- and sericite-phyllites, calcareous phyllites and some quartz-phyllites; limestones.
(ii) 'Unwashed' association—flaggy quartzites; quartz-sericite-phyllites, quartz-chlorite-phyllites and some quartz-phyllites.
(iii) Dark limestone/dark phyllite association—Shira Limestone assemblage.
(iv) Grit association—Tom Dubh grits and the grits immediately below the base of the Crinan Grits.

The 'clean-washed' association is characterised by a general lack of micaceous and chloritic debris representing the silt or clay fraction of the original sediment; calcite is frequent. In contrast, the 'unwashed' association has abundant chloritic debris and the original sediments of this association must have been largely impure sands, silts and clays. These two distinct associations probably represent variations in the source of the sedimentary material and in the conditions of deposition.

The dark limestone/dark phyllite association of the Shira Limestone represents sedimentary conditions with more restricted circulation, and a general lack of exogenetic detritus. The grit association is the precursor to the overlying Crinan Grits.

5. CRINAN GRITS

The base of the Crinan Grits rests upon the Craignish Phyllites with only slight disconformity over most of the district. However, in the north of the area, the boundary is less regular and there is a wedge-shaped extension of the Crinan Grits protruding southwards along the strike into the outcrop of the Craignish Phyllites (Fig. 2). This relationship is not tectonic in origin, but was apparently caused by the contemporaneous deposition of the two distinct lithological types. Most of the Crinan Grits are made up of massive beds of grit, often graded and sometimes showing flow-markings. The grits are coarse-grained (0.02 to 0.1 inch) and composed of subangular fragments of quartz and felspar in a matrix of chlorite, sericite and calcite; they are intercalated with thin, dark phyllites. Two distinct zones of flaggy, laminated, dark-coloured phyllites, ranging between 50 and 200 feet in thickness, occur interbedded with these grits (cf. Allison, 1940, 428).

These flaggy zones are occasionally associated with limestones and closely resemble the Shira Limestone assemblage.

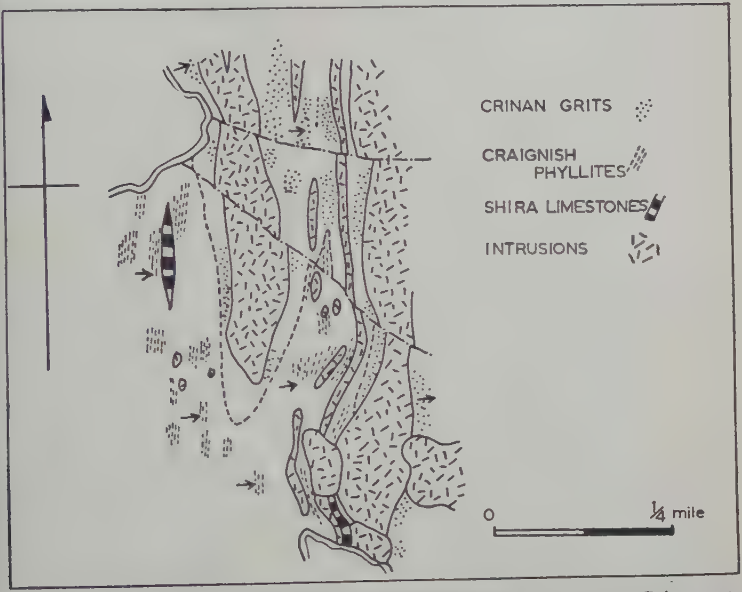

Fig. 2. Relationship between the Craignish Phyllites and the Crinan Grits, east of Kilmelfort

Two changes are present in the upper part of the Crinan Grits in the north of the district. A lenticular zone of pale green tuffs outcrops on both sides of Gleann Mor; these were referred to by Symes (1899, 49) as 'bedded epidiorites' but are not mentioned in the subsequent memoir covering this area. The grits above this volcanic group are very much darker than normal owing to a predominantly chloritic matrix. This change may have been caused by the deposition of fine-grained volcanic debris during the sedimentation of the grits.

6. GLEANN MOR LIMESTONE GROUP

The Gleann Mor Limestone Group lies conformably on top of the Crinan Grits in this district (in the Loch Awe Syncline as a whole, the Tayvallich Limestone occurs above the Crinan Grits). A local name has been used during the present investigation because there are two essential differences between the Tayvallich and Gleann Mor Limestones. Firstly, there is the possible anomaly between the thickness of the Crinan Grits on the east and west sides of the Loch Craignish–Gleann Domhain line. Secondly, the Gleann Mor Limestone, in the area mapped, does not contain any igneous bodies of clearly extrusive origin, in contrast to the abundant lavas present at this horizon throughout much of the Loch Awe Syncline (Bailey, 1913).

This group is composed of a succession of inter-bedded flaggy dark limestones and phyllites. The beds of limestone are often massive and vary in thickness from one half-inch to twenty feet. Oolitic limestones are occasionally present, but owing to the extent of recrystallisation can only be seen in thin section (Allison, 1940, 434).

7. MODE OF DEPOSITION

During the field investigation, the attitude of all flow structures which indicated the direction of the currents depositing the sediment were measured and mapped; some of these data are shown in Fig. 1(b). Care has to be taken when these structures are examined, firstly, because similar structures may be developed by folding and, secondly, because they have been tilted from their original attitude. It is thus necessary to measure the current-bedding or flow markings on joint or bedding surfaces and then, by use of a stereographic net, to transfer the bedding to the original position.

The variability of the Craignish Phyllites and the nature of the associated sedimentation structures suggest that this group represents the deposits of an epicontinental sea marginal to a land-mass. The currents which deposited the Craignish Phyllites were derived from the north-north-west and north-west, which suggests that land was probably in that direction. In marked contrast to this, the grits forming the greater part of the Crinan Grits are derived from the north-north-east; the divergence of these two current directions is brought out in Fig. 1(b).

An examination of thin sections from these two horizons suggests that there were original petrological differences between the two source areas from which the detrital material was derived. For example, the Crinan Grits contain grains of perthite, fragments of a basic igneous rock and accessory sphene. In contrast, the Craignish Phyllites contain none of these, but are characterised by an abundant blue-green tourmaline. Blue, opalescent quartz has been observed in both the Craignish Phyllites and the Crinan Grits, but is much more abundant in the upper group; Sutton & Watson (1955, 129) have discussed the significance of the blue quartz found in the Dalradian of the Banffshire coast.

A further point of interest is that the sequence of lithological changes visible in the upper part of the Craignish Phyllites appears to be carried on through the flaggy zones of the Crinan Grits into the Gleann Mor Limestone Group; these changes are the decrease in grain-size of the phyllites, the disappearance of quartzites and most of the exogenetic detritus and the appearance of dark phyllites and dark limestones. Such a series of changes could be associated with an environment which became progressively more isolated from the supply of land-derived material. Eventually, only extremely fine-grained detritus was spasmodically washed into the area to form thin beds of dark muddy silts intercalated between calcareous muds.

As no current directions have been observed in the flaggy zones of the Crinan Grits or the Gleann Mor Limestone Group, the derivation of these horizons is inferred from the unity of the environmental changes in these two groups with similar changes in the upper part of the Craignish Phyllites. Thus, while the conditions of deposition of the north-westerly derived material were changing, there were spasmodic influxes of gritty debris, probably derived by density currents, from the north-north-east. It is possible that these two distinct phenomena are related and that the progressive isolation of the area was associated with the development of a NNE.–SSW. trough; the direction of flow of the grits would be controlled by the orientation of this trough. When grit sedimentation ceased, the area was far removed from the land-mass to the north-west and dark muds were laid down under conditions of restricted circulation.

This demonstration that successive sedimentary formations have been derived from different directions is important, because it has a considerable bearing upon palaeogeographic interpretations based solely upon flow structures or lithological changes. The parallelism of flow structures in greywacke-type deposits to the later tectonic 'b' direction is becoming more frequently noted in the published literature (ten Haaf, 1957). It is apparent that much sedimentary material of this type was deposited in troughs or basins running parallel to the inferred palaeogeographic coastlines. At the same time, the marginal shelf facies extended out from the coastline and interdigitated with or overlaid the trough facies. This situation is clearly present in the Lower Palaeozoic succession of Wales where flow structures in some greywackes (Wood & Smith, 1957) indicate deposition parallel to the geosynclinal trough while palaeocurrent observations in the shelf facies indicate that these deposits were derived from the marginal parts of the sedimentary basin.

As yet, there is insufficient palaeocurrent data from the Dalradian to extend the present observations beyond the area mapped. However, the continuity of grit horizons associated with frequent graded bedding, within the Upper Dalradian of the Highland Border and Donegal, suggest that the mechanism of deposition described in this paper may have wider significance.

ACKNOWLEDGMENTS

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DISCUSSION

DR. J. G. RAMSAY asked Dr. Knill whether he thought that the methods that he had employed for establishing the original orientation of the sedimentation structures were completely satisfactory. The method by which the tectonic effects have been removed by rotation of the beds into a horizontal position about their strike was only applicable to rocks which have undergone simple flexure and where there was no internal deformation. The author has recently described a 'similar' folding of some of the rocks in the area, a fold style which produces thinning of the beds in the fold limbs. The slaty cleavage within the phyllites also indicated internal deformation, and although no such cleavage was seen in the thick units of current-bedded grit was the author absolutely sure that they were sufficiently undeformed as to justify his methods?

Although the errors that may arise by incorrect unfolding may be very large the speaker did not think that this would be so in the examples described by Dr. Knill.

Since the meeting Dr. Knill has kindly made his observations available to the speaker so as to compare the results of the two methods of unfolding. The maximum divergence in direction between the two methods was 10°, and in most of the examples the divergence was less than 5°.

PROFESSOR SUTTON congratulated Dr. Knill in particular on the evidence he had obtained on the directions from which the sediments in the Craignish area had come. With regard to the point raised by Dr. Ramsay he thought that, as in the Craignish area, the results fell into two consistent groups, and as some of each of the two groups of measurements were taken from rocks which were deformed in the same fashion, the way that Dr. Knill had arrived at his results was a valid one.

Some of the evidence known to the speaker from the Upper Dalradian rocks in Banffshire where the style of deformation varied considerably might well require reinterpretation in the light of Dr. Ramsay's comments.

It was of interest to see how ideas first put forward by Sir Edward Bailey from his work on the Dalradian were subsequently employed to interpret younger rocks and that now the resulting new ideas on the origin of greywackes established from the study of these more recent rocks can be applied in their turn to the interpretation of the Dalradian.

DR. PITCHER said that he was particularly impressed by the identity in lithology between the strata described by Dr. Knill and their most probable equivalents in Ireland. Thus the Craignish Phyllites and Crinan Grits were represented by the Glengad Schists and Crana Quartzite in Inishowen and by the Termon Green Schists, Gorteen Lough Striped Schists and Kilmacrenan Grit much farther to the south-west. Sedimentation structures were present throughout this long outcrop and Dr. Knill could extend his studies for some 120 miles and still be reasonably certain of working in the same stratigraphic horizon.

PROFESSOR J. H. TAYLOR said he has listened to Dr. Knill's interesting paper with pleasure. The author's interpretation of the sedimentary structures in the Crinan Grits as aligned parallel to the axis of the basin of deposition was in harmony with the evidence from other geosynclinal sediments. In fact the speaker knew of only one formation, the Oligocene Grès d'Annot of the Alpes Maritimes, in which structures of this kind had been shown to be extensively developed normal to the axis of the geosyncline.

The trend of sedimentary structures formed in epicontinental seas was, however, less easy to interpret. Currents on the continental shelves today flowed along the coasts rather than at right angles to them. W. F. Tanner as a result of studies of the false-bedding in Cretaceous sediments of the south-eastern United States concluded that certain of these had been deposited by littoral currents almost parallel with the shoreline.

Much of the recent American work on palaeocurrents had been carried out on formations which were fluviatile coastal plain sediments rather than shelf sediments. This applied, in large measure, to the Mississippian and Pennsylvanian rocks of the east and central United States studied by Potter, Pelletier and others and to some at least of the Pre-Cambrian quartzites of the Lake Superior region investigated by Pettijohn. In such deposits a generalised current-bedding direction indicating transport normal to the shoreline was to be expected.

The Craignish Phyllites and the Gleann Mor Limestone, however, bore no resemblance to fluviatile sediments and the author's interpretation of them as deposits of an epicontinental sea seemed fully justified. The speaker wondered if he could support his conclusion that they were deposited by seaward flowing currents by any independent evidence, such as facies change in the inferred offshore direction.

DR. STURT exhibited several photographs of sedimentary structures from the Loch Tummel district of Central Perthshire, and commented upon the fact that even in these relatively high-grade metamorphic rocks sedimentary structures such as graded and current-bedding, slumps, convolute bedding, sedimentary laminations, bottom structures and sedimentary dykes are well preserved in certain quartzite horizons. These structures have not been preserved in the majority of the more pelitic sediments.

On behalf of DR. N. RAST, Dr. Sturt said:

'Dr. Knill's paper, judging from the abstract provided, contains much that is interesting. The study of currents in the Dalradian rocks is a relatively new development and is likely to provide much information about the palaeogeographical conditions of deposition of these rocks. Several points, however, must be made in correlating the Craignish area with the surrounding district.

'The current direction in the Crinan Grits, deduced from large-scale current-bedding, is, as Dr. Knill discovered, generally from the NNE. Farther south, however, there are indications of a change in current direction. At Kilmory Bay the coarse grits above the phyllites show currents flowing from SSW.

'The small-scale ripple current-bedding in the Craignish Phyllite is not a reliable index of the overall current direction, since variations at any particular point are often too extreme to indicate the true current direction.

'Finally does the author consider that current directions invariably point at the provenance of the sediments concerned, and, if so, is there any petrographic support for such a hypothesis?'

In replying to the discussion DR. J. L. KNILL agreed with Dr. Ramsay in that care had to be taken when reorientating directional flow structures in deformed rocks. The tectonic effect had been removed, firstly, by the rotation of the local fold axis to the horizontal and then by tilting the beds into a horizontal position. All the sedimentary structures used in the palaeocurrent study occurred in the quartzites and grits, which had suffered concentric folding; the similar folding, referred to by Dr. Ramsay, occurred in the phyllites, which contain few sedimentary structures beyond the depositional laminations. Little internal deformation was visible in the more massive horizons and sedimentary structures occurring in obviously deformed rocks were not measured. In consequence, the author felt justified in the method of reorientation which had been adopted.

The author thanked Dr. Ramsay for his examination of the palaeocurrent data, made after the meeting, and was glad to hear that the maximum divergence in direction, between the two methods of unfolding, was 10°. It appeared likely that, in this area, variations in palaeocurrent direction would be the result of changes in sedimentation rather than differences in the style of folding.

The author was intrigued by Professor Sutton's remarks on the development of ideas in geology; it would be of even more interest to watch the continued evolution of this general subject during the next ten or twenty years.

Dr. Pitcher's comparisons between the Loch Awe succession and the sequences developed in Donegal were of value. The author and his wife were engaged in a study of the sedimentation of the Dalradian rocks of Inishowen and it was hoped, eventually, to extend this work farther to the south-west.

Professor Taylor's comments on the relationship between current directions, sedimentary facies and palaeogeography were of great interest. The complete sedimentary pattern in the Craignish Phyllites, based upon the orientation of current-bedding, flow markings, overturning of slumps and the form of the lenticular quartzites appeared to suggest a derivation from a land-mass to the north-west. Unfortunately, the tectonic structure did not allow one to follow any particular horizon in the offshore direction for any distance and no evidence of facies changes developed normal to the inferred shoreline had been established. However, the Craignish Phyllites reappear ten miles to the south-east on the other limb of the Loch Awe Syncline; the author was mapping this fold limb and it was hoped to present the evidence for this area at a later date.

The similarities in the rock-types and sedimentary structures, referred to by Dr. Sturt, to those developed in Central Perthshire were interesting. In higher-grade metamorphic rocks the tectonic deformation was clearly greater, and so the interpretation and reorientation of sedimentary structures in this terrain would be more difficult than in the Loch Awe area. In particular, the method of reorientating palaeocurrent data, when polyphase folding had occurred, must be very stringent and limited observations were not likely to give significant results. In this connection, the techniques devised by Dr. Ramsay, referred to above, were likely to be of importance.

Dr. Rast's observation of a south-south-westerly derived palaeocurrent direction associated with the Crinan Grits at Kilmory Bay was very welcome because it tended to confirm the author's suggestion that this group was deposited in a NNE.–SSW. trough. Density currents would tend to flow in either direction along this trough depending upon the source of the currents and the axial slope of the trough. The author pointed out that in the Craignish–Kilmartin area, the direction of flow of the Crinan Grits had been largely determined from the form of flow-markings and not from large-scale current-bedding. The author agreed that there were variations in the orientation of the current-bedding in the Craignish Phyllites but did not consider these variations to be extreme. During the mapping of Craignish, it became clear that there was a consistency in the dominant direction of derivation of the sedimentary material that made up the Craignish Phyllites, as deduced from current-bedding; as mentioned in reply to Professor Taylor's remarks, current-bedding was not the only criterion used for determining the palaeocurrent direction. The relationship between current direction and provenance was too great a topic to discuss merely in relation to such a limited area. The author believed that the Craignish Phyllites were derived, more or less directly, from a land-mass to the north-west of the present outcrop. The provenance of the Crinan Grits is uncertain as they may have been derived either from the margins or the terminations of the trough, or from ge-anticlinal ridges within the sedimentary basin; extensive field and microscopic studies may be necessary before a solution to this problem can be found. There are certain petrographical variations, described in the paper, which give support to the concept of a different provenance for the Craignish Phyllites and the Crinan Grits.

The Basal Rock Surface on Weathered Granitic Rocks

by BRYAN P. RUXTON and LEONARD BERRY

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ABSTRACT: Near, or at, the base of the weathering profile on granitic rocks there is often a very rapid, sometimes sudden, change to massive bedrock. The upper limit of the bedrock is designated the Basal Surface. The basal surface does not demarcate the limit of weathering. Above it more highly weathered material allows ready access to sub-surface water while below it the slightly weathered bedrock is much less permeable. When open structural surfaces are confined to near the surface, rapid or prolonged weathering may be expected to develop a well-defined basal surface, regular on sheeting structures and irregular on blocky jointing.

Basal surfaces exhumed by erosion may bear evidence of their origin, e.g. the presence of well-rounded corestones *in situ* on their surfaces. A careful distinction should be made between exhumed basal surfaces and similar surfaces cut by surface agents of erosion.

1. INTRODUCTION

IN DISCUSSING the problem of tors in Britain, Linton (1955, 476) claimed that a tor is a residual mass of bedrock produced below the surface by a phase of profound rock rotting effected by groundwater and guided by joint systems. This is followed by a phase of mechanical stripping of the incoherent products of chemical action. He states that '. . . tors may rise sharply from a basal platform of bedrock which may be flat or inclined and is interpreted as representing the position of the water-table during the period of rock-decomposition, so that tor height cannot exceed the depth of the vadose zone of that period'.

Following Linton the authors, from studies in Hong Kong (1957), concluded that 'A thin vadose zone . . . would cause a concentration of weathering activity and a mature profile would be expected to develop rapidly; perhaps with a well-marked basal surface'. We also noted that '. . . many local sections indicate a definite lower limit to active weathering which is sometimes marked by a very rapid change to bedrock'.

The purpose of this paper is to show that if the term 'basal platform' is changed to 'basal surface' and the latter redefined, a useful concept is introduced into geology.

2. DEFINITIONS

A platform is 'a raised level surface' (*Oxford English Dictionary*) and the term is unsuitable for a feature which is formed under the ground surface. The adjective 'basal' makes the compound term illogical, while the term 'platform' is already widely used in its proper sense.

A surface is defined as 'the limits that terminate a solid' (*Oxford English Dictionary*). We shall consider the solid to be a mass of solid rock inclusive of any structural surfaces whether open or not but exclusive of any weathered debris. The basal surface is then basal in respect of the main mass of weathered material and at the same time defines the upper limit of dominantly unweathered rock. The basal surface is like some other geological contacts—sometimes regular, sometimes intricately irregular, and at all times susceptible to ready generalisation.

For some purposes it may be necessary to refer to the actual basal surface, and for others a generalised basal surface will suffice. The solid rock below the basal surface need not delimit weathering activity, though it may serve as a very close approximation to it.

Attention is confined to basal surfaces formed by sub-surface weathering in frost-free regions, though similar conditions will probably occur elsewhere.

3. THE BASAL SURFACE

Study of the basal surface has some important applications. Firstly, the pattern of incipient weathering below the generalised basal surface reveals the structural characteristics of bedrock and to some extent predicates the future path of weathering and erosion. Secondly, a detailed knowledge of the basal surface is vital to any engineering project requiring solid bedrock for foundations. Thirdly, apart from a few closely jointed or sheared zones in granitic rocks the only important sub-surface water bodies are found in thick masses of its weathering debris overlying deeply buried basal surfaces (Enslin, 1956). Finally, specimens of solid rock collected from anywhere but a little way below the basal surface may not be completely fresh specimens. Any alteration in them may or may not be due to weathering but cannot be automatically assumed to be exclusively the result of hypogene alteration.

Wide variations in the position and characteristics of the basal surface will occur dependent on climate, rock structure, topography and geomorphic history. We shall consider three types of basal surface developed on sheet-jointed granite, blocky jointed granite, and in the area of a shatter belt (Fig. 1). Convex hills were chosen for illustration because numerous examples of this type occur in Hong Kong and excavations have supplied sections on which our diagram is based. In flatter areas and wide valley courses conditions will not be the same. Nevertheless, it seems a

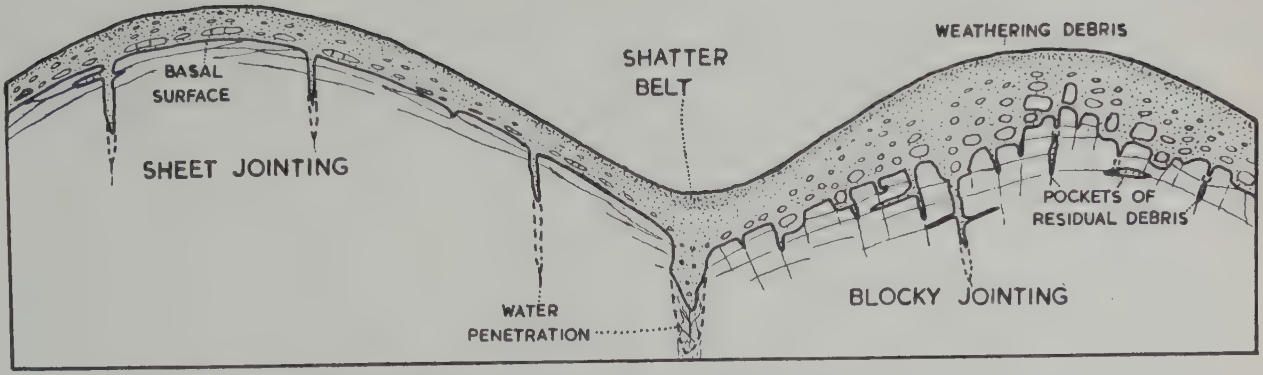

Fig. 1. The weathering profile on convex hills of granite in an area of sheet jointing, blocky jointing and a shatter belt

general rule that weathering profiles on granitic rocks are deeper when open joints are more numerous near the surface, and deepest along shatter and shear belts. If sheet joints are confined to, or open only near, the ground surface then a convex hill undergoing intense and rapid weathering will develop a dome-like basal surface. In this case the structure largely determines the position of any recognisable water-table which may or may not develop as weathering proceeds. The water-table does not always determine the position of the basal surface. If rainfall is light and weathering slow the quaquaversal dips on the sheet joints tend to allow a rapid dispersal of any sub-surface water and the concept of a water-table need not be involved in a theory of the formation of a basal surface.

On a convex blockily jointed hill with open joints extending some way beneath the surface, circulation of any sub-surface water will depend on the network of intercommunications between the joint-blocks. Weathering and the basal surface will be highly irregular in the early stages. Deep weathering may take place along fracture zones, or masses of greater joint intensity. Later the sub-surface network of joints is integrated owing to weathering along them and a water-table may develop in the weathered debris as in any other permeable material. After an integrated water-table has developed further weathering will be restricted mainly to the vadose zone. The resulting basal surface will be irregular in detail though in some cases it may approximate to a smooth surface.

Observations in Hong Kong and the Sudan indicate that sheet jointing often underlies a zone of blocky jointing whenever this ceases at depth and this is indicated in Fig. 1. In many instances the upper sheets are thinner than the smallest diameter of the overlying joint-blocks and corestones.

Any zone in which a massive granitic rock has been fractured and shattered attracts and channels sub-surface water and weathers to greater depths than the surrounding areas. The limiting factor to active weathering in this case is probably the depth to which a vigorous mixture of gas and water is maintained. The basal surface in this belt may be expected to be intricately irregular and possibly indistinct.

4. EXHUMED BASAL SURFACES

Under constant conditions of climate, slope, geomorphic position, rock susceptibility and erosion, the basal surface will have a definite form and will occur at a certain depth below the ground surface. A change in the rate of erosion or in the relationship between weathering and erosion will either increase or decrease the depth of the basal surface. In some circumstances the removal of the residual debris will become more rapid than the further extension of the weathered mantle. Then lower and lower zones of weathering will be exposed until the basal surface is stripped of its overlying material and becomes exhumed.

The recognition of such exhumed surfaces is important as with a little sub-aerial modification they may closely resemble other bare rock surfaces formed by sub-aerial erosion. Diagnosis is possible if the surface retains patches of the former weathering profile above it as they may retain characteristics indicating a sub-surface origin.

Evidence from Hong Kong and the Sudan suggests that granite breaks up in different ways according as to whether it is exposed at the surface or buried within residual weathering debris. Beneath the surface joint-blocks are usually attacked on all sides at once from the outside inwards, giving rise eventually to well-rounded corestones by spheroidal weathering. If erosion rapidly removes the residual debris from around such a block any incipient spheroidal scaling will be completed but no more will occur.

A cuboid joint-block, a sheet 'tablet' or a well-rounded corestone once on the surface may break up in a variety of ways which have never been analysed in detail. These always seem to include cross-fracturing and granular disintegration.

Any bare rock surface mantled by well-rounded corestones, some of which can be proved to be *in situ*, is an exhumed basal surface. But one small patch of corestones on a wide rock plain is not sufficient evidence on which to base a theory for all the plain. It is only evidence of the former presence of one small area of overlying weathering mantle. A small hill on a plain could be weathered and then rapidly stripped giving rise to these conditions (Fig. 2). Thus though a large expanse of bare rock surface may be interpreted as an exhumed basal surface, this can only be proved if abundant corestones rest upon it.

In both regions studied some small granite domes have been explained as exhumed basal surfaces. In Hong Kong the domes recorded are mostly

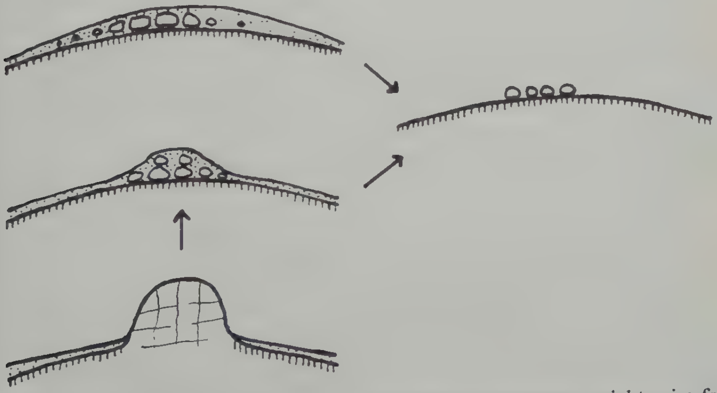

Fig. 2. Showing how an isolated patch of well-rounded corestones might arise from different original conditions

small islands where severe marine erosion has oversteepened the coastal slopes and most of the weathering mantle has been removed by mass sliding. In the Sudan they are often near the centre of structural compartments and have been stripped by sheet and rill wash.

The variety of landforms that may be exhumed from a very thick weathering mantle is considerable. In Hong Kong this mantle varies in thickness from nothing to 300 feet and complete stripping would reveal surfaces with considerable relief. Owing to the tremendous difference in the resistance of the weathered zones and the slightly weathered bedrock to erosion the basal surfaces seem to be little modified during the stripping. Many rocky headlands are clearly stripped basal surfaces just beginning to suffer from direct marine attack.

In arid and semi-arid regions the pediment has often been thought of as a cut rock surface veneered with migrating debris. It is not at all clear whether an original bare rock surface cut by the agents of erosion is variably buried under migrating debris and then variably weathered; *or*, whether weathering debris *in situ* and upper migrating material are reclining on a basal surface which is locally exposed by virtue of its own irregularities or by excessive local erosion. Both types could be present in any one pediment area. We hope to pursue this suggestion further in a future contribution.

CONCLUSION

The upper limit of solid rock beneath the main mass of weathered debris on granitic rocks is here called the *Basal Surface*. This is usually irregular in detail but regular when generalised. For engineering excavations and detailed geological study it may be vital to delimit the actual basal surface as accurately as possible, while for most purposes a generalised basal surface will suffice.

In localities undergoing excessive erosion or very slow weathering, or both, the basal surface may be exhumed. This bare rock surface may retain well-rounded corestones *in situ* on its surface testifying to its subsurface origin. Intense weathering accompanying or followed by severe erosion stripping the residual debris from parts of the basal surface is a common form of denudation in Hong Kong.

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The Origin and Development of Surface Depressions in the Mendip Hills

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ABSTRACT: This study aims to provide a systematic classification of the numerous types of sinkhole mentioned in the morphological literature.

As three types of stream sink are readily identifiable from their morphological relationship with a valley, the main part of the investigation is concentrated upon enclosed circular depressions of other origin. Two hypotheses, formation by surface solution and formation by collapse into underground cavities, were tested in the Mendip Hills. No evidence has been found to support the idea that surface solution can form circular sinkholes.

Collapse sinks of different forms have been arranged in a developmental sequence. The four stages of the karstic cycle have been redefined, coupling the same visual criteria as used before with a new rationale of process and development. This rationalised version of the karstic cycle suggests that Cheddar Gorge is more likely to have originated as a surface valley than by the collapse of underground caverns.

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1. INTRODUCTION

ENCLOSED DEPRESSIONS, which, according to W. H. Hobbs, 'constitute one of the best surface indications of limestone country', have been widely recognised as significant index features. S. W. Wooldridge (1937) describes them as 'the essential unit in karst topography', and O. D. Von Engeln (1942) echoes this opinion in the phrase 'the initial and fundamental unit of karst'. Depressions have also been variously cited as criteria for recognising the several stages of the karstic cycle, and their morphological importance has been repeatedly affirmed.

As yet, however, very little serious study has been accorded to them, and nineteen authors of geomorphological textbooks are able to produce almost as many different views on their formation. These views co-exist without controversy: some writers seem unaware that discrepant ideas have been expressed elsewhere. One invokes solution along joints by percolating rainwater, a second believes solely in collapse of cave roofs, and a third considers that stream seepage, past or present, is the effective cause. Half a dozen authors combine solution and collapse in different ways, three suggest solution and stream erosion, while another prefers streamwork and collapse.

It appears that three types of depression—stream sinks, solution sinks and collapse sinks[1]—are believed to exist. However, only one geomorphological textbook in the English language describes all three types. Two speleological works mention them, but the most systematic expositions are in French by E. de Martonne and P. Macar. Very little attention is paid to any possible development of morphology: forms are described as genetically distinct without considering the possibility that they may be only different stages of the same feature. A further symptom of the neglect which these depressions have received is the fact that only two writers, W. H. Hobbs and L. C. King, adduce any actual evidence in support of their ideas.[2]

There is clearly scope for research, both because so little work has been done hitherto, and also because such depressions are key features in limestone areas. As a further point of interest they are also found in great profusion on certain non-calcareous rocks (F. J. North, 1929, and T. Thomas, 1954). Detailed study of a particular locality suggested itself as the most useful type of enquiry in the present state of our knowledge, and the Mendip area was selected because it offers a variety of structural, lithological and morphological milieux which it was hoped would facilitate a comparison of the factors affecting the depressions.

Examination of Criteria Previously Suggested for Classifying Depressions

It was originally intended to classify each hole as it was mapped, but this idea had to be abandoned after realising that the classification criteria advanced in the literature are not only contradictory from author to author, but are also frequently incompatible with field evidence in the Mendip area. This may be demonstrated most simply in the case of stream sinks.

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[1] It has been argued that, as solution creates caves and is thus the indirect cause of collapse sinks, there is little point in distinguishing this type from solution sinks. It is considered valid, however, to contrast sinks due to *surface* solution with those due to *deep seated* solution followed by *surface collapse*, because the two types develop differently.

[2] There are innumerable terms for depressions and a selection is listed below. Many have been defined in mutually contradictory senses by different workers. The three terms used here are virtually self-defining and explicitly state the causes they invoke.

Aiguigeois, avaloir, aven, betoir, bois tout, borne, buso, centripetal basin, chaldron du diable, circular depression, clot, cloup, creux, doline, emposieux, entonnoir, gat, goule or goulle, gouffre, gour, hundiemento, igue, inglutidos, jama, katavothra, kuniste ankil, maidelles, marmite de geants, orgeln, oules, ponor, pozzo, rogage, ruphista, shake hole, sink, sinkhole, slocker, sluggy, sncoir, solution hollow, solution subsidence, solution pan, sotch, swallet, swallow hole, tindoul, turlough, valley sink.

De Martonne and Macar describe stream sinks, or avens, as subcircular in shape, usually smaller than solution sinks, and always deeper than wide. They normally resemble rocky wells or chimneys opening down into a mass of limestone, but a hint is also given of intermediate forms grading towards the funnel-shaped solution hollow. English writers, G. T. Warwick and the Stride brothers, have quite different ideas, possibly because they deal with the intermediate forms mentioned. The distinguishing feature which they stress is the asymmetrical shape caused by the stream valley leading in on one side. In other respects these stream sinks resemble solution sinks and there is no question of their being deeper than wide.

In the field there is found to be a complete gradation between depressions swallowing quite large streams and circular holes which are asymmetrical only by virtue of a small gully torn out in one side. Most of these inlet valleys are dry for substantial periods of the year, are quite short and originate perhaps in the middle of a field. It does not seem feasible that such tiny and intermittent drainage courses can have been responsible for forming the depressions, which are often very many times larger than they. It is more reasonable to suppose that the depression formed first and then acted as a local base-level, capturing what had previously been diffuse surface runoff, and concentrating it into one, two or more centripetal gullies. These gullies would naturally enlarge and erode headward, but even in the case of quite large ones it appears that they merely use pre-existing depressions and did not form them. A few cylindrical shafts of the aven type also exist on Mendip but these are completely unassociated with streams. These observations reinforce the idea that while streams may come to occupy such holes, they are not necessary for their origin.

True stream sinks cannot be entirely dismissed however. They do occasionally occur, in both an active and dry condition. They are sited along the thalwegs of the larger valleys, as is compatible with their original position in the bed of an appreciable stream, and possess 'hanging' dry valleys left abandoned on the downstream point of engulfment. They will be discussed in a later section.

Since the vast majority of the Mendip depressions do not belong to the stream sink category, they must be either collapse or solution sinks. It is frequently asserted that the latter are by far the more abundant type, but this is difficult to substantiate on the basis of the existing evidence. For example, P. Worcester attributes only deep circular pools to the agency of solution. But the more commonly held opinion is that solution sinks develop on level or gently sloping ground where rapid surface runoff is impossible and the maximum amount of rainwater is directed towards underground percolation. The joint spaces and bedding planes are thought to widen by solution. Where two joints intersect, percolation of rainwater is facilitated and erosion is more active, giving rise to spaces. The overlying debris mantle is believed to settle down into these, and light depressions appear at the surface. These are gently rounded shallow basins. They concentrate the runoff towards their centres, and so stimulate the solution process. Consequently the hollows are thought to deepen and widen.

Developments from this point are outlined in widely divergent opinions, but attention may now be turned to collapse sinks. These are holes formed at the surface as a result of underground subsidence. Macar describes the rough subvertical sides of such collapses and Worcester states that an ensuing change is the slumping of the soil or mantle rock around the rim. The hole gradually smooths over and becomes less deep. Soil creep clogs up the bottom and may in fact render it so impermeable that a sinkhole pond can be held perched high above the regional water-table. The pool silts up and the hole is gradually completely filled.

A problem has now crystallised. It is claimed that one set of holes, solution sinks, are deepening and widening; while another set, collapse sinks, are diminishing in size as they infill. Both sets of features look much alike, and co-exist on the same rock type, and in the same conditions of rainfall and weathering. Yet they are held to be developing in diametrically opposite modes. It is a situation of curious conflict which stimulates a closer examination of the criteria cited for distinguishing the two types.

(*i*) *The Criterion of the Cross Profile*

W. D. Thornbury asserts that solution holes develop slowly without physical disturbance of the rock or any break in the soil and vegetation mantle. In collapse such disturbance is inevitable and bare rock would be exposed in the sides. This seems to offer a foolproof distinction, but there are at least three situations where the distinction is not in fact clear.

First, if collapses eventually smooth over they reach a stage where they appear never to have been disturbed, and so resemble solution hollows. Secondly, A. Holmes claims that as solution progresses and the pipe widens, loosened joint blocks will fall in, and the surface will break, at least in the bottom of the depression. The criterion of a continuous soil mantle is thus invalidated. De Martonne describes such a composite feature as a *doline percée* and transfers it from the solution to the collapse category. A third point is that rocky sides alone cannot prove formation by collapse until the possibility of a stream sink has been eliminated. We must not, therefore, place too much reliance on smooth or broken form as a criterion of origin.

(*ii*) *The Criterion of Outline or Shape*

Shape has also been employed as a criterion. Hobbs states very firmly that whenever a depression has a characteristic circular outline there can be little doubt that it is the product of solution, whereas those formed by collapse are oval or less regular in shape. But Worcester believes subsidence holes are circular and N. Hinds describes elongated or irregular solution depressions dependent on the relative strengths of different joint systems. This is the exact reverse of Hobbs's views. Clearly shape has not yet been established as a criterion.

(*iii*) *The Criterion of the Material in the Depression*

Hobbs points out that where solution is dominant the soil mantle should be shallowly underlain by solid rock interrupted only by a small descending crevice or pipe. Collapses, however, should be occupied by a mass of limestone rubble. King, also, describes the aggregate of broken rock fragments found in certain S. African examples and the jagged toothed outcrops left on the depression sides. These differences seem logical, but unfortunately are not to be detected visually except in the case of fresh collapses. Old smoothed-over features would be indistinguishable from young solution hollows, without the assistance of a spade. Similarly the joint systems which are so widely invoked cannot be verified by mere surface inspection.

The unhelpful state of the literature regarding classification criteria stems from the fact that textbook authors have included depressions for the sake of completeness but have had few original observations to draw on. It was therefore decided to approach the field evidence in the Mendip area without reference to predetermined criteria.

2. THE ORIGIN AND DEVELOPMENT OF DEPRESSIONS IN THE MENDIPS

Six main lines of investigation were undertaken in the area selected and are summarised below. Each produced results which converge upon the same conclusion, namely that there is abundant proof of the existence of collapse sinks but no evidence in support of solution hollows.

(a) The Testimony of Local Witnesses

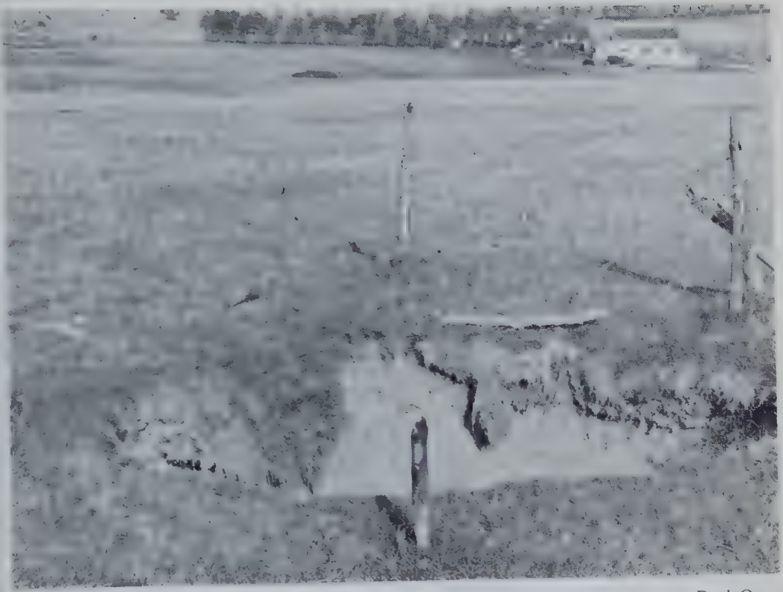
Whereas solution hollows would probably grow too slowly to be noticed, a number of witnesses were able to describe sudden collapses, some occurring spontaneously and others as a response to additional load such as the passage of a plough. Several cases, dated between 1946 and 1955, were examined in the field. Their forms were in harmony with the postulated origin and could also be arranged in a developmental sequence according to age. The most recent were vertical-sided cylinders with bare rock and soil exposed round the sides, and the turf of the sunken centre was still visible in the bottom. They were several feet in diameter. Older collapses departed progressively further from the simple cylinder form. The sides had crumbled and weathered back and debris had covered the turf in the bottom. Widening and shallowing had thus combined to convert the cylinder into a funnel-shaped or cup-shaped depression. These fresh collapses occurred where the limestone is covered by Triassic marls or Lias clay, but similar development has also been noted in undated holes in limestone.

(b) The Morphology of the Depressions

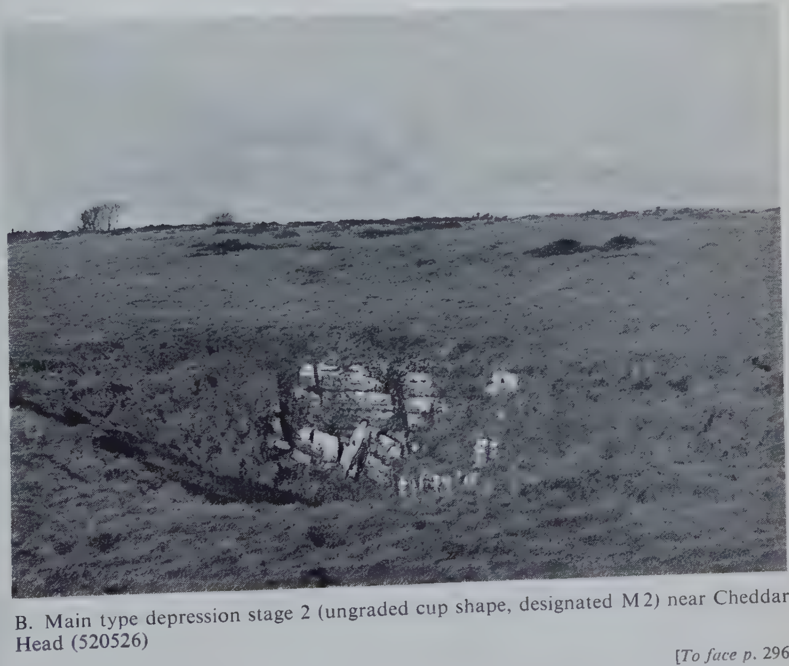
Secondly, the other depressions of the area were examined and notes made on their morphology. The data were then analysed to ascertain whether the development sequence established for the fresh holes could logically be extended through all the examples. Altogether nearly a thousand depressions were examined in the Mendip region, all of which can be grouped into the types and stages shown in Fig. 1.

Cylindrical holes, Main type, stage one (designated M 1) are an initial form (Plate 4 A) and are relatively rare. They occur on various outcrops, the most notable example being a fifteen-foot shaft. For this and similar pits the only explanation can be collapse. However, smaller subsidences occurring naturally within pre-existing depressions cannot be so definitely attributed to collapse alone. They may, in fact, represent secondary settling within an older collapse feature, but an alternative explanation is provided by the *doline percée* concept, i.e. that the pipe existing beneath a solution hollow has been enlarged so much that it can no longer support the floor of the hollow and a breach occurs. If this is so, collapse must be regarded as a proximate cause only, the ultimate cause being solution. Summing up the M 1 stage evidence it is clear that some depressions are certainly collapse sinks whereas others may be due to either collapse or solution. Other lines of evidence are needed to prove which.

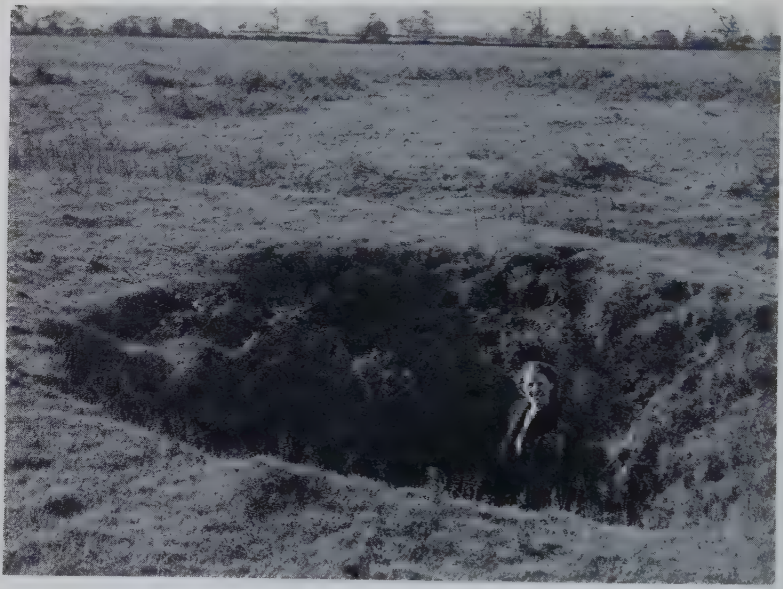
An important example of the roughly cup-shaped main type second stage, designated M 2, is provided by Wurt Pit (31/559539), which is forty-eight feet deep. This is surrounded by a cornice composed mainly of Carboniferous limestone but also incorporating a feather edge of Lias limestone on the north. Below this rim the sides are smoother, being largely formed of debris slopes which merge together to give a concave floor. Wurt Pit demonstrates the process by which a vertical collapse shaft may be transformed into a cup-shaped hollow, a process described by A. Wood in his analysis of the weathering of a cliff or 'free face'. The base of the free face is buried by debris first and the upper part is progressively covered as the debris grows higher. The rims therefore tend to remain more rugged than the floor. Where secondary subsidences have occurred in depression floors the reverse may be true. Thus the collapse mechanism is able to account for both those cases where the upper slopes are rougher than the lower and also those where the floors are more broken.



A. Main type depression stage 1 (cylindrical collapse designated M 1) near Red Quar (562516). Initiated in 1946 and photographed in 1955



B. Main type depression stage 2 (ungraded cup shape, designated M 2) near Cheddar Head (520526)



A. Main type depression stage 3 (graded cup shape, designated M 3) at Valley Wood (586494)

B. Main type depression stage 4 (saucer shaped, designated M 4) at Red Quar (563515)

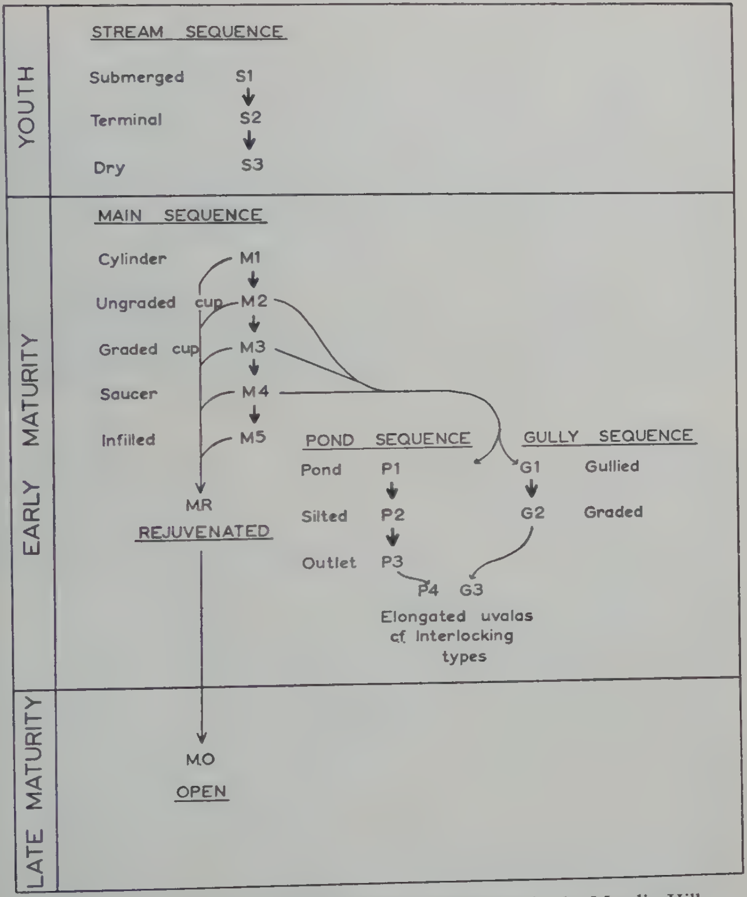


Fig. 1. The inter-relationship of karstic depressions in the Mendip Hills

The solution mechanism can only give rise to the latter condition as solutional activity is bound to be strongest in the bottom of the cavity. Once again it appears that collapse is competent to account for all cases whereas solution could account for only a fraction, and even for these is not proven.

During phase M2 vertical faces are reduced but slopes remain ungraded (Plate 4B). In limestone they consist of free faces and debris slopes. In weaker rocks the irregular profile is maintained by slumps and landslip scars. But eventually these more active mass movements reduce the slope to an angle at which they themselves cease to operate and cede their dominance to the gentler process of soil creep.

With or soon after the supervention of soil creep comes a smooth-graded profile which is the criterion of phase M3 (Plate 5A). Further evolution is likely to be gentler and slower but it maintains the same trend towards widening and shallowing. Presently a saucer-like form replaces the cup form: this is phase M4 as illustrated (Plate 5B). At M5 infilling is complete, and to the undiscerning eye the ground is now levelled flush. But in the autumn the nuances of grass colour still bring back a faint reflection of the cycle which has run its course and faded away.

The great majority of the Mendip depressions can be referred to one or other stages of this simple main sequence. The remainder fall into other series which may be termed the pond sequence, the gully sequence, the stream sequence, interlocking forms and rejuvenated forms. In these, as also in the main sequence, each type of depression which has been classified is capable of field identification by purely visual criteria.

(*i*) *The Pond Sequence*. The normal infilling of collapse sinks may produce an impermeable floor coating and hence a perched water-table. Rainwater cannot readily percolate and gathers as a pond, from which moment the development of the depression departs from the main sequence. This stage may be designated P1.

The presence of a pond causes downwash to be spread out in a flat sheet instead of being disposed in the concave curve of dry depressions. A simple silted flat-floored depression ranks as P2. It is suggested in the literature that flat-bottomed forms develop where the rocks are horizontal, especially where an impermeable layer is reached, or where the water-table is high enough to intersect the bottom of the hollow. The probability of such influences is not contested, but there is little opportunity for their operation in the Mendip area where the water-table is everywhere too deep and there is little horizontal bedding. Therefore some other cause must be responsible. The infilling process suggested seems likely partly because it is known to operate in any case, and partly because it could cause a gradual decrease in permeability and thus account for the appearance of intermittent ponds at first and perennial ponds later.

The silting completed at P2 marks a change of process. On flat ground excess water seeps away into the surrounding soil, but on slopes the level of the pond may rise to the lowest point of the rim, when the water escapes and cuts an outlet channel. A depression with a pond possessing such an outlet has been designated P3.

Phase P4 is reached when downcutting has integrated the levels of two or more linked hollows and so produced an elongated form or blind valley, with or without a marshy floor. This is in a sense an end stage, caused, not by infilling as at M5 and P2, but by disguise as a valley which comes to bear no recognisable relationship to circular depressions. A closely similar form marks the end of the gully sequence also. These two are juxtaposed on Fig. 1 and are discussed jointly below.

(*ii*) *The Gully Sequence*. Turning from outlet to inlet channels, a further variation is recognised where depression walls have been modified by one or more gullies. These generally occur on sloping ground and are commonest with the larger depressions which command a bigger catchment area. They seem to develop most readily where the holes are cup-shaped. The initial condition may be called G 1 passing to G 2 where the gullies are graded.

Once established the gullies can deepen and erode headward to produce an elongated pseudo-valley, designated G 3, similar to that reached in P4. The latter may be distinguished by the fact that it heads accordantly in a circular depression, whereas the gully either does not head in such a form or does so discordantly.

(*iii*) *Interlocking Forms*. In addition to G 3 and P4 there is the rather special but quite common case of multiple, or interlocking, collapse, where several shafts originate at such close quarters that their walls intersect one another as they open out. The party wall is thus made much lower than the outside edges, so that the individual sinks merge into one roughly continuous collapse. As the units are often aligned rather than grouped, they form an elongated depression resembling condition at G 3 and P4 but with a less graded floor. The subsequent histories of all three kinds appear to be similar. If they remain virtually dry, they may go through the various phases of infilling outlined in the main sequence. On the other hand it is possible that where they occur on impermeable cover rocks they may acquire streams which grow in length and permanency. In time these streams would cut down into the underlying limestone and pass into the stream sequence discussed below.

(*iv*) *Rejuvenated Forms*. To complete the description mention must be made of rejuvenation forms. Rejuvenation can occur at any of the stages enumerated as a superimposed collapse giving depression-within-depression topography. This simply sets back the cycle to condition M 1 over a part of the area of the sink.

(*v*) *The Stream Sequence*. Whereas the pond and gully series are simple modifications of the main sequence, the stream sequence exists independently in its own right. It begins from its own initial surface, a stream valley, and proceeds to the formation of stream sinks which are quite unconnected with collapses.

In a young area streams must flow over permeable and impermeable beds alike. While a surface valley is being excavated there is also a gradual solution of stream bed joints and crevices to a size capable of swallowing appreciable quantities of water. At the stage of thalweg 1 (Fig. 2) part of the stream disappears at weak points (A), (B) and (C). These sinkholes cannot easily be detected as they are submerged beneath the water. This stage may be designated S1. On enlarging, however, these three sinks may consume the whole stream between them. This stage is represented in thalweg 2 in which (A) has become a terminal active sink, and is designated S2, found at the terminus of a blind valley. The former continuation, now a dry bed, sometimes perched high on the downstream side of the S2 amphitheatre. The sink itself is usually a rocky shaft or inclined rift.

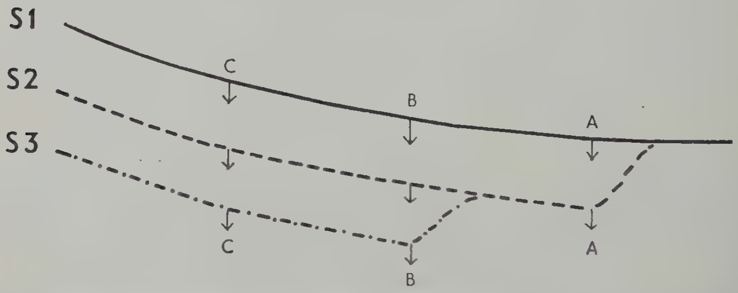


Fig. 2. Stages in the evolution of the valley profile and stream sinks of a disappearing stream on limestone

Sinkholes (B) and (C) continue to enlarge until they can absorb the whole flow and leave (A) dry, producing condition S3. The complete process is well illustrated in the Longwood Valley, one of the head reaches of Cheddar Gorge. Of four recognisable stream sinks the highest is of the submerged type S1 and only in time of drought can the water be seen disappearing into the bed. Below this point are two active terminal sinks S2 which feed into the cave, Longwood Swallet, and still farther downstream is a dry depression of type S3.

Stream sinks of types S2 and S3 are rare in the Mendip Hills, and this fact may be used to estimate the probable abundance of solution hollows which have so far figured only dubiously in the analysis. Both streams and solution sinks form and enlarge as the result of percolating water, but whereas the latter depend on gentle solution coming at intervals, the stream swallets undergo continuous solution by large and steady water supplies. Moreover, they are also subject to corrasion. Of the two types, therefore, the stream sinks should be larger, and per unit area more numerous. Even after desiccation they still hold the advantage of runoff from the valley slopes, whereas solution features would receive only local supplies. Thus it seems improbable that solution sinks would be very abundant.

All the depressions mapped in fact fit logically into the stream sink or collapse categories, and it would be an economy of hypotheses to discard the idea of solution sinks altogether. But since many authors regard them as common features, more definite evidence is needed before this economy can be established.

Finally, mention should also be made of the open collapse, type M0, where no core of collapsed material remains to plug the bottom of the hole and daylight is admitted straight down to the underground stream. None of these open collapses has been observed in Somerset, but they are of general importance as a diagnostic feature of late maturity in the karstic cycle.

(c) The Evidence of Depth–Diameter Ratios

Solution hollows developing without physical disturbance of the vegetation mantle would probably maintain a constant angle of rest for their sides. That is, the depth–diameter ratio would be fixed within narrow limits, and the points plotted on a graph should cluster closely along a straight line for any given type of rock. Possibly, however, as the hole grows and rainwater is progressively concentrated towards its floor, deepening might outstrip widening, culminating in the *doline percée* stage. The plotted points might then trend along a curve rather than a straight line.

No such trend would be expected in the case of collapse hollows which may in the initial stages have any depth—the fresh cylindrical holes of recent date were from one to fifteen feet in depth, older features such as Wurt Pit being deeper still. Diameters may also vary considerably in size and the infilling process would perpetuate a wide range of ratios.

The depths and diameters of a large number of depressions in selected areas in the Mendips were measured accurately to the nearest foot with a surveyor's tape during the field work. The results of one such set of observations made in three large fields near Priddy Hill are graphed in Fig. 3. A completely random scatter is revealed and the same result emerges for other areas. The affinity is clearly with a collapse origin, and solution features must be either entirely absent or at the most so rare that they can cause no recognisable trends in the graphs.

(d) The Evidence of the Infilling Material

The various types of depression have been defined in terms of visual criteria which permit direct identification in the field. But other evidence such as the nature of the infilling material was also taken into account while devising the classification.

It is now possible to expand the simple argument that solution sinks

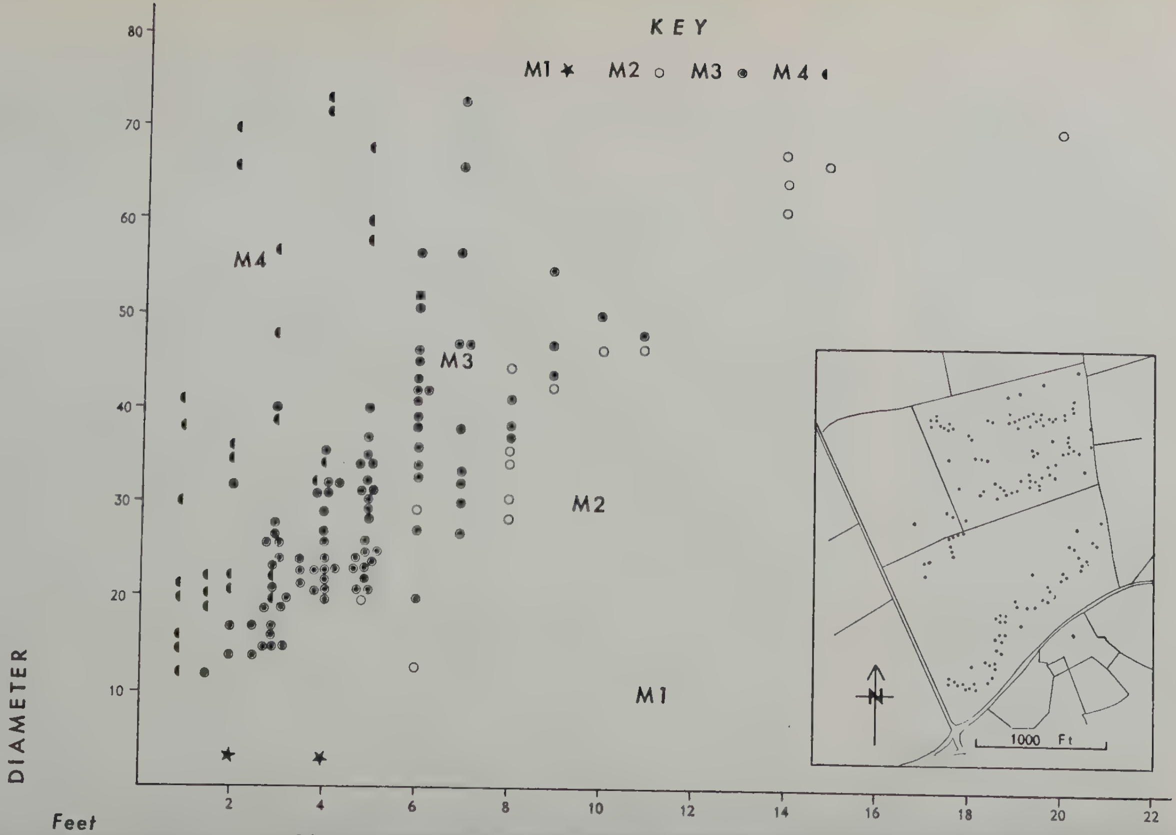


Fig. 3. Depth–diameter relationships and the evolutionary stages reached by depres-

contain only a thin coating of soil over solid rock, while collapse sinks hold a mass of coarse broken rubble. At condition M 1 and M 2 such rubble would indeed be dominant, but at M 3 and M 4 soil creep causes progressively finer layers to overly the rough debris. There would be a definite vertical grading in the calibre of the infill, and this condition would be directly related to the form of the depression and its stage of development. But it can be revealed only by digging.

This is an important consideration because it throws light on what has so far been the weakest link in the argument, namely the nature of the holes at M 3 and M 4. It must be borne in mind that the Stride brothers proposed a developmental series almost identical with M 1–5, but in reversed order and attributed to solution mechanism. Were this true digging would soon reveal a shallow rock basin, but if collapse is the real explanation, the trench or shaft would proceed to a great depth through progressively coarser material.

In fact three radial trenches of up to three feet depth, and post-hole auger borings of up to seven feet depth, made across six depressions, revealed a tendency for finer material to grade downward into coarser. The limited depths, however, precluded a conclusive interpretation. Fortunately there exist records of several speleological excavations in these depressions, extending down eighty feet in one case, and often reaching a cave in the bottom (e.g. Hunter's Hole, 31/549502). Frequent mention is made in these records of progressively coarser rubble and boulders, and the speleologists have learned to dig in the side, rather than the middle of depressions, to hug the support of the rock wall, and avoid the loose and dangerous collapse core. Occasionally the excavations tailed off into a narrow pipe, but the overwhelming weight of the evidence is for an origin by collapse.

(e) The Surface Relationship of Pipes

An examination of the pipes which are sometimes said to give birth to solution hollows is also illuminating. There are over fifty limestone quarries in the Mendip area, and between them they provide 170 pipes for examination. The pipes are infilled with various kinds of material but predominantly a reddish clay which, according to the solution hypothesis, should be a residue derived from that overlying limestone which was dissolved away to form the hollow.

But not one of these pipes is associated with any trace of a surface depression at its upper end. It appears therefore that although solution along vertical joints and faults is a widespread mechanism it need not produce surface depressions. The sites where solution hollows are specifically expected thus fail to provide them, and points to the conclusion that these features do not exist at all in the area.

(f) The Evidence of the Distribution

A further test which can be applied is the nature of the distribution pattern. Solution hollows result from an agency which works from above downward: they should therefore occur only where the limestone outcrops, and there one might expect a distribution as even as the rainfall. Collapse sinks on the other hand are due to an agency which works from below. They would occur only where caves had already been developed, and would thus show a patchy distribution especially along lines of underground drainage, which in fact they do. They could also be transmitted upward through an impermeable cover rock, and indeed a remarkably high proportion of Mendip depressions are found on Mesozoic outcrops. Since these rocks are insoluble, surface solution is here an impossibility.

Thus all six lines of evidence lead towards the abandonment of the solution hypothesis, and the acceptance of collapse to account for the vast majority of Mendip depressions, the remainder being stream sinks.

3. EVIDENCE FROM OTHER AREAS

The elimination of the solution hypothesis in the Mendips solves the conflict described in an earlier section. No longer is it necessary to try to reconcile two directly opposed processes operating simultaneously in the same conditions. The question can now be asked whether the conclusion is universally applicable. The full answer must await the accumulation of data from other areas, but meanwhile the authors have been able to make some corroborative observations in other parts of Great Britain and Europe.

Chalk country provides an excellent test-case because few natural caves are known and collapse does not immediately appear to be a likely mechanism. The surface depressions of the chalk are generally assumed to be solution hollows. In reality, however, collapses do occur. In 1952 there appeared in the flood-plain of the River Mole opposite Box Hill, a small cylindrical collapse exactly similar to some seen in the Mendip Hills. Near by was a rather older but still subvertical feature, filled with a bramble bush. As both of these were formed in insoluble sandy alluvium they must have originated over some cavity in the underlying Chalk.

The most spectacular feature in this neighbourhood is the so-called 'Policeman's Hole' (51/171534) produced on a winter's morning in 1947 when a thirty-foot elm-tree suddenly disappeared into a shaft forty to forty-five feet deep. Water rising from below mounted nearly to the lip of the shaft, suggesting that the tree roots were impeding a cavernous stream passage. It is significant that this inferred cave occurs in the same district as one of the few natural caves known in inland chalk (51/159522). A connection between surface depressions and caves is further supported by the fact that surface sinks are aggregated into definite localities, such as the Mole Valley, the Isle of Thanet and Béthune in France.

Further corroboration of the collapse origin of circular depressions may be drawn from the north side of the South Wales coalfield, which has recently been studied in detail by T. Thomas (1954, 1955). The innumerable depressions on the limestone are nearly equalled in frequency and outclassed in size by similar features on the Millstone Grit. These latter at least cannot be due to surface solution. Originating at depth, they have in some cases been transmitted through very great thicknesses of grit—exceptionally to over 200 feet. Thomas assumes them to be collapses, and invokes a similar origin for the depressions on the limestone areas also.

Pipes and photographs of pipes in many areas have been examined, and cases as far apart as Jamaica, U.S.A., Britain and Yugoslavia all tell the same story. The dissolved pipe is plugged with infill so that its surface lies flush with the surrounding country, and no surface depressions have been noted. It seems that surface solution beneath the soil has in all these instances been sufficiently slow to permit contemporaneous infilling of the pipe with soil and debris.

The present writers have not themselves seen any true circular solution depressions. The evidence that they exist at all must therefore be drawn from others. Hobbs gave a brief description of sections through such hollows in Yugoslav railway-cuttings, but the most explicit evidence was contained in a private communication to the authors by Dr. M. Sweeting. This describes hollows with bare rock walls and floor, and no trace of a collapsed core, seen in Yugoslavia and the French Causses. These could only have been formed by surface solution. They are generally quite small, not exceeding ten feet in depth. Dr. Sweeting adds that she does not believe that solution depressions occur commonly in north-west Europe, and that she too would class the Mendip sinks as collapse features.

Drawing together all the evidence the following tentative hypothesis may be advanced: collapse is by far the most common cause of enclosed depressions in limestone country, while surface solution is so slow a process that only in soil-less areas can deepening outstrip infilling and produce a visible landform. In such bare areas deepening may be restricted after a certain period owing to the formation of protective scree or solution residue. Collapse sinks would not only be more common but also frequently larger than solution sinks. It would be desirable for these conclusions to be tested in other areas.

4. CYCLIC SIGNIFICANCE OF THE COLLAPSE HYPOTHESIS

The opposed views as to the predominance of solution or collapse must be associated with opposed corollaries as to the development of the karstic cycle.

Cvijič outlines four stages in the cycle. The stage of youth is marked by a gradual transference of surface waters to underground channels, and a few depressions make their appearance. In early maturity all surface water is swallowed by abundant dolines and uvalas which are now the dominant relief features. In late maturity a decline sets in as roof collapses expose stretches of cave passage to form new open valleys: while in old age rivers again flow on an impervious substratum. These four stages are defined respectively by drainage net, solution features, collapse features and stratigraphical horizon, a rather heterogeneous collection of criteria.

Any depressions due to *surface solution* should theoretically begin as soon as rain falls on the area, and they should develop during the stage of youth. Von Engeln describes them as the initial and fundamental unit. Once established they would continue to enlarge and there seems no reason why they should ever disappear, as long as any limestone remains. They should characterise virtually the whole of the karstic cycle. But in practice they are not nearly so common as this hypothesis would suggest and large stretches of limestone are free of them. The claim that they are initial units conflicts even with Cvijič's view that few develop during youth and even more with Davis's contention that all are delayed till early maturity. A further difficulty lies in the statement that dolines and uvalas swallow water which would otherwise have been surface runoff: this statement carries an implied conclusion that until such depressions have appeared cavern formation cannot begin in earnest and caves must post-date depressions. Thus, while depressions could occur without caves, caves would not occur without depressions. This situation is not borne out by observation.

The *collapse* hypothesis by contrast not only accommodates the existing observed facts of the cycle, but is also able to throw additional light on its development. Caves are a necessary preliminary to collapse, therefore cavern formation must pre-date depressions. The whole stage of youth is available for the process. This accords with the observation that in some areas caves exist where there are no depressions, and also for the fact that the converse cannot be safely asserted, even for Chalk. This order of development can be logically argued on other grounds. At the surface, rain can percolate through thousands of fissures, dividing its action between them and so producing only slight effect upon each one. At depth, however, a stronger and more continuous action takes place. This is true both in the phreatic zone where the dissolving medium is always present, and also in the vadose zone above, where the water is concentrated into streams flowing along lines of weakness. In any given time, therefore, cave development is likely to make more progress than the solution of fissures near the surface.

Bearing this in mind we might therefore modify the various karst stages as follows. In *youth* caves are forming underground but are as yet so small that no collapses occur. Stream sinks can form, however, as the drainage progressively passes underground, and they are probably all dry at the end of the stage except where external streams sink at the beginning of the limestone outcrop or are able to maintain themselves allogenically across it. In *early maturity* the caves have enlarged sufficiently to cause collapse at individual points, resulting in depression. By the end of this stage the surface cover of depressions may be practically complete. In *late maturity* the caves are greater still so that collapses are now large enough to expose lengths of cave passage to the open air. By *senility* they are so great that no cave streams remain roofed over at all. The limestone is now reduced to interfluvial ridges and later to isolated hills.

In this way the four stages are based on a single progressive development, the size of caves, and upon the visible differences which cave growth produces at the surface. This is less arbitrary than the assorted criteria normally used, but the actual stages remain the same in terms of diagnostic surface features. The scheme follows Davis in excluding from the youthful stage the few depressions which Cvijič claimed heralded the greater profusion of early maturity. It also allows for the case in which senility is brought on within the limestone by erosion down to the water-table, as well as the classic but more special case of erosion down to an underlying impervious bed. And thirdly this restatement of the cycle immediately explains why late maturity is commonly reached in Yugoslavia where caves are large, and is absent from the Mendip Hills where caves are still relatively small.

The stream sequence is a feature of youth, although sinks at the limestone margin may remain active even until the onset of senility when all underground valleys have been exhumed. The collapse sequences are features of early maturity reaching their end stages of infilling or disguise as valleys within the same period. Thus many individual depressions may go, but rejuvenation and fresh collapses maintain and gradually intensify the pitted state of the surface during the whole of early maturity. The maximum size of collapses should also increase, as the caves enlarge.

The Mendip area is partly in the stage of youth and partly in early maturity. No single example has been found of an open collapse typical of late maturity. It seems unreasonable therefore to suggest that any senile features exist: yet this is precisely what is being claimed when it is asserted that Cheddar Gorge is a completely deroofed cave system. It seems more reasonable to regard Cheddar Gorge as a simple youthful valley which has recently performed the typically youthful action of abandoning its surface course for a subterranean one. It is thus in perfect harmony with the stage reached generally throughout the area; and this also holds good for Burrington Combe.

The close attention which has been given to small surface details of a selected area of limestone has thus led directly to the need for a revision of existing ideas on the Karst cycle as a whole.

ACKNOWLEDGMENTS

The authors wish to express their gratitude to Mr. H. Murrell, Professor L. S. Palmer and Professor E. K. Tratman for local information; to the Mendip quarry owners and managers; to Dr. M. Sweeting and Dr. T. M. Thomas for information on other areas, and to the following students for assistance in the field: Misses K. Allington, C. Mann, S. Molyneaux and G. Pica; Messrs. J. Brown, I. Davis, J. Davis, D. Glading, I. Jackson, D. Morris, D. Patterson, M. Schofield, D. Smith and J. Stevens.

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DISCUSSION

MR. P. EVANS, after congratulating the authors on their paper, drew attention to the numerous instances of collapse in beds immediately overlying the Chalk in Hertfordshire and Middlesex. He also refered to sinkholes on the Shillong Plateau, Assam, India, mentioning an instance where blockage of an underground channel (presumably at least in part due to collapse) led to the accumulation of water in several sinkholes on the plateau. The breakdown of the barrier led to a flood in the valley, many hundreds of feet below, where the system of channels discharged.

THE AUTHORS in reply thanked Mr. Evans for his contribution to the discussion and for describing the collapse features in Hertfordshire and Middlesex. These depressions, which could also be traced elsewhere in the Chalk, notably in Kent, appeared to add further support to the argument advanced in the paper.

Frost-heaved Soils of Barrow, Rutland

by L. F. CURTIS and J. H. JAMES

Received 6 March 1958; taken as read 5 June 1959

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ABSTRACT: An exposure of disturbed soils occurring upon the Lower Estuarine Series of the Inferior Oolite at Barrow, Rutlandshire, is described. The disturbances are attributed to frost heaving and possible processes leading to their development are discussed.

1. INTRODUCTION

SOILS DEVELOPED upon the Lower Estuarine Series of the Inferior Oolite commonly show vertical variation in the texture of soil horizons, due largely to the fact that the Estuarine Series is made up of thin bedded clays, sands and silts. The underlying Northampton Sand is an economic iron ore deposit mined by open cast methods and soil profiles based upon the Estuarine Series are frequently exposed in the workings. During a visit to a site worked by the United Steel Company, near Barrow, Rutlandshire (Grid Ref. 43/896152) in 1956, unusual soil profiles were observed which the authors ascribe to the phenomena of frost heaving. Eventually this section will be destroyed as mining operations progress, therefore it was considered desirable to record details of the soil profiles present and discuss possible processes leading to their development.

2. DESCRIPTION OF THE SOILS

The general arrangement of the structures present in the section is shown in Fig. 1.

The topsoil (a) of dark brown (10YR/4/3) sandy loam has a uniform depth of eleven inches and is separated from the underlying material by a very sharp boundary. Beneath the topsoil, pockets (b) of yellow brown (10YR/6/8) sandy clay loam–sandy loam and reddish brown (5YR/5/6) sandy loam are embedded in a grey (2.5Y/7/2) clay (c). The pockets are readily distinguishable from both the topsoil and the juxtaposed clay by colour and texture differences.

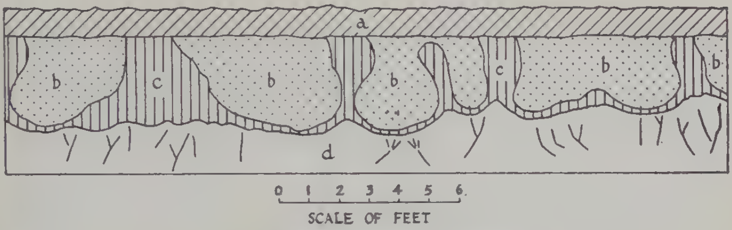

Fig. 1. Sketch of part of Section

a. Topsoil; b. Pockets of yellow brown and reddish brown material; c. Grey clay; d. Laminated clays and sands

Beneath the grey clay which surrounds the pockets there is an horizon (d) composed of partly weathered clays and sands of the Estuarine beds. This horizon is thrown up into a series of undulations and varies in thickness from fifteen to twenty-one inches. The crests of the undulations are sharply defined and are interposed between the pockets, whereas the troughs are located beneath the pockets.

The pockets are sharply truncated by the horizontal lower boundary of the topsoil. Although they have somewhat irregular forms the pockets are mostly rounded in outline in horizontal and vertical sections. Some tubular pockets occur and in a few instances the grey clay constricts the pockets just below the topsoil resulting in pear-shaped outlines in the vertical section. The pockets are usually symmetrical in outline when viewed normal to the section, although some asymmetrical pockets are present. Asymmetrical examples in the section do not appear to have any preferred orientation suggestive of large-scale solifluxion. The pockets vary in size from two to eight feet in width and from two feet six inches to three feet three inches in depth.

Part of the section (see Fig. 2) has been examined in greater detail and sampled for mechanical analysis. Pocket A (Fig. 2) is infilled with yellow brown material (b2) of fairly uniform grain size as is shown by histograms 3 and 4 (Fig. 3). The fine sand content of this pocket is large, ranging between 55.8% and 70.1%, whereas the silt and coarse sand fractions are small in amount. In the adjoining pocket B (Fig. 2) yellow brown soil, similar to that occurring in pocket A, encloses a core of coarser material (b1) which is reddish brown (5YR/5/6) in colour; the grain size composition of this core material is markedly different from that of the yellow brown deposit which surrounds it and also differs substantially from the overlying topsoil (a). (Compare histograms 1, 2, 3, Fig. 3.) The main differences lie in the coarse sand fraction; the core material contains 42.8% coarse sand, the topsoil 16.4% and the yellow brown material approximately 4%.

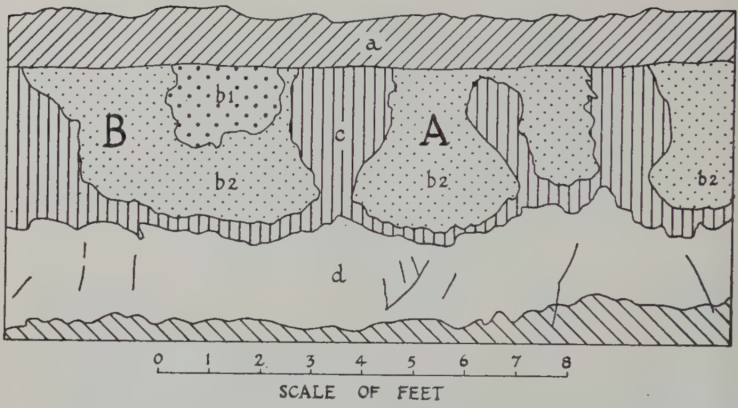

Fig. 2. Vertical Section

a. Topsoil; b1. Reddish brown sandy loam; b2. Yellow brown fine sandy clay loam; c. Grey clay; d. Laminated clays and sands

Table I clearly indicates the texture differences between the pocket material and the juxtaposed grey clay. The fine sand fraction of the clay layer is about half that of the pocket material, whilst silt shows a threefold increase and clay is approximately doubled. The grain size pattern of the weathered Estuarine beds underlying the clay layer is similar to that of the pockets. (Compare histograms 6, 3, 4, Fig. 3.)

TABLE I. **Particle Size Composition of Horizons Expressed as Percentages**

Horizon	Coarse Sand 2–0.2 mm.	Fine Sand 0.2–0.02 mm.	Silt 0.02–0.002 mm.	Clay less than 0.002 mm.
Topsoil (a)	16.4	51.7	14.9	17.0
Reddish brown pocket material (b1)	42.8	29.7	6.0	21.5
Yellow brown pocket material (b2) at a depth of (i) 17–25 in.	5.2	55.8	8.2	31.0
At a depth of (ii) 31–36 in.	3.4	70.1	7.5	19.1
Grey clay (c)	4.3	24.2	26.1	45.4
Laminated clays and sands (d)	1.1	63.2	6.7	29.0

Examination of the soil fabric of the grey clay horizon revealed structural cracks parallel to the peripheries of the pockets. In the troughs below the

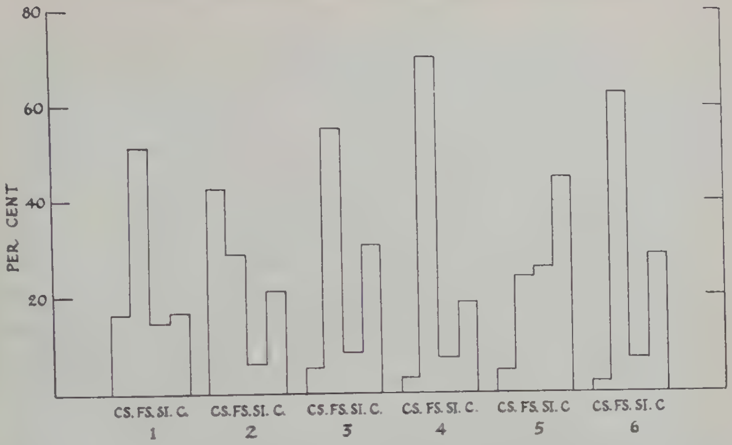

Fig. 3. Histograms of mechanical composition

1. Topsoil; 2. Reddish brown pocket material; 3 and 4. Yellow brown pocket material; 5. Grey clay; 6. Laminated clays and sands. CS. Coarse Sand; FS. Fine Sand; SI. Silt; C. Clay

pockets cracking is almost horizontal, changing gradually to vertical prismatic cracking as the perimeter of the pocket is followed upwards to the base of the topsoil. The partly weathered clays and sands of the horizon (d) underlying the grey clay are strongly laminated. Vertical cracks present in this horizon occur most frequently beneath the crests of the undulations.

3. DEVELOPMENT OF THE SOIL PROFILES

From the observations made it would appear that, before disturbance, the horizons were in the following order of superimposition:

Horizon 1. Pocket material of reddish brown sandy loam	(b1)
Horizon 2. Pocket material of yellow brown fine sandy clay loam ...	(b2)
Horizon 3. Pale grey clay	(c)
Horizon 4. Grey laminated clays and sands	(d)

The existing topsoil has been cultivated and probably consists of a mixture of the deposits brought to the surface by disturbance. In order to account for the present arrangement of the subsoil structure some mechanism must be envisaged providing differential movement between contiguous beds. It is unlikely that soil flow could have been the mechanism involved since the section is cut in a level site and the nearest valley slope is 400–500 yards distant. Moreover, no former significant change of slope is postulated within this distance in an account of the pre-glacial topography of the area by Kellaway & Taylor (1952). Furthermore, the subsoil structures displayed in the section are generally symmetrical in form and show little evidence of the type of distortion or attenuation associated with soil flow. The term 'head' as defined by Dines *et al.* (1940) does not therefore seem to be applicable to the structures under discussion, nor can they be ascribed to the phenomena of 'trail and under-plight' as described by Spurrell (1886). It is considered therefore that frost heaving must have been the agent responsible for the formation of the structures.

Freezing of Horizons 1, 2, 3 and 4 would result in different amounts of ice segregation in the various textural horizons. Furthermore, the clay horizons of the lower part of the profile would undoubtedly result in development of a perched ground-water table, thereby providing available water for the formation of ice layers. In this connection it should be noted that, at the present time, the lower horizons of the profile display the characteristic orange-brown and grey mottling associated with periodic waterlogging. Freezing and thawing of the soil surface would not be homogeneously distributed but localised centres of freezing would develop related to plant cover and micro-relief features.

The uppermost layer (Horizon 1 (b1)), consisting of coarse sandy loam, would show little ice segregation since it contains large voids and the grain size composition does not favour capillary rise. On the other hand, Horizon 2 (b2), being composed of fine sandy clay loam, would begin to segregate ice at various points due to its suitable mechanical composition. The greatest amount of ice formation would, however, occur in Horizon 3 (c) due to its fine texture and high water capacity. Repeated freezing and thawing would lead to progressive deformation of the textural horizons and relative movements would be accentuated by variable growth of ice crystals as irregularities in the boundary between Horizons 2 and 3 developed. The present arrangement of the structures suggests that heaving in Horizon 3 was sufficiently strong to force material of this layer upwards into the overlying horizons and eventually through to the surface as a mud boil.

The authors would like to acknowledge the help given by Mr. C. L. Bascomb in carrying out the mechanical analyses.

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Upper Devonian Ammonoids from North-West Dartmoor, Devonshire

by MICHAEL R. HOUSE

Received 9 March 1959

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ABSTRACT: Ammonoids indicative of the Platyclymenia, Clymenia and possibly Wocklumeria Stufen are described from the area north-west of Dartmoor.

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1. INTRODUCTION

THIS REPORT is intended to give the ammonoid evidence bearing on the Devonian succession and stratigraphical divisions recently established by Butcher & Dearman (1959) in the region north-west of Dartmoor. The new faunas listed or described herein were mostly collected by Mr. N. E. Butcher, Dr. W. R. Dearman and the writer. The ammonoids have served to give useful stratigraphical dates to the rocks termed the 'Transition Series' by Butcher & Dearman (1959, 6) which, in the area north-west of Dartmoor, occur as inliers within the Culm Measures. The new faunas will be described according to the succession established by these authors and detailed notes will be given on the more interesting specimens. All the material mentioned has been presented to the Geological Survey Museum, London, to which the prefix 'G.S.M.' refers.

2. PALAEONTOLOGICAL DESCRIPTIONS

(a) The Manor House Beds

Locality. Stream bed north of the Manor Hotel, Lydford Station, at a spot 280 feet NW. of the 646-foot bench mark on a bridge north of the station (50208324).[1]

The specimens found here first by the writer were all poorly preserved, but probably imitoceratids (G.S.M. Zi 8331–4). Subsequently Mr. Butcher has collected the following:

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[1] All Grid references lie in the 100 km. square 20 (SX).

Imitoceras cf. sulcatum (Münster)

Plate 6, 1, Fig. 1 d

Description (of G.S.M. 87250). Specimen 8 mm. in length, representing an incomplete pyritic mould. At about 9.2 mm. diameter the whorl width is estimated as 6.5 mm. Shell form sub-globular, with two preserved constrictions which indicate a frequency of about five constrictions in the last whorl. The suture, traced with difficulty, is illustrated in the accompanying diagram (Fig. 1 d).

Remarks. The shell form and suture pattern show that the generic assignment is correct but the specimen is too poorly preserved for certain specific determination although it agrees best with *I. sulcatum.*

Platyclymenia (? Pleuroclymenia) sp.

Plate 6, 2, Fig. 1 b

Description (of G.S.M. 87251). The specimen is an incomplete fragment which, at *c.* 10.5 mm. diameter, has a whorl width of *c.* 4.9 mm. and an umbilical width of *c.* 5.2 mm. Shell form is evolute, with a wide umbilicus. Whorl section (Fig. 1 b) is depressed and sub-reniform. The whorl flanks are ornamented by strong ribs, projecting forward, which number five in 3 mm. on the mid flanks at *c.* 8.2 mm. diameter. Trace of the ribbing almost disappears over the ventro-lateral shoulder, but a slight salient can be observed there. Over the venter is a broad and shallow sinus. The suture is not well seen but apparently forms a broad, gently rounded lobe over the lateral flanks and a wide and shallow saddle over the venter. The dorsal suture has not been seen.

Remarks. This specimen, whilst clearly referable to the genus *Platyclymenia* on the basis of shell and suture form, is too small for adequate comparison with the numerous described species of the subgenera *Platyclymenia* ss., *Pleuroclymenia* and *Trigonoclymenia.* However, the ornament does not show the parabolic ribbing characteristic of *Trigonoclymenia* (Schindewolf, 1934, 341), and the subdued sutural elements are more suggestive of *Pleuroclymenia* than *Platyclymenia* ss. This is supported by the depressed and sub-reniform cross-section which is typical of the inner whorls of *Pleuroclymenia* although it may be remarked that the inner whorls of many of Wedekind's species of *Platyclymenia* ss. remain unknown.

These ammonoids represent the only fossils known to date from the Manor Hotel Beds. The genus *Platyclymenia* is restricted to the Famennian Platyclymenia Stufe according to Schindewolf (*in* Moore, 1957, 43). The association with *Imitoceras* suggests correlation with the upper part of that division since Matern (1931, 123) has shown that these genera are commonest in Oberdevon 4 and, at least in the Dill-Mulde, are rare or absent in the lower Platyclymenia Stufe.

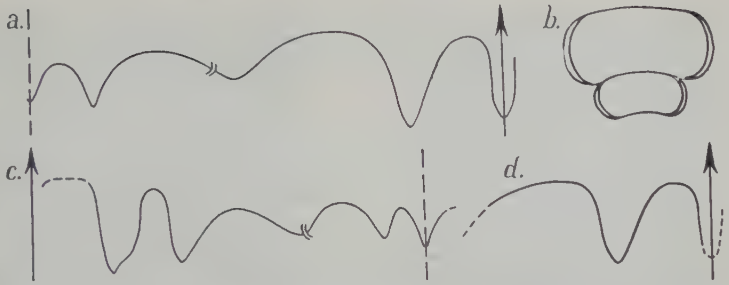


Fig. 1a. *Imitoceras sulcatum* (Münster). Diagram of suture based on G.S.M. 57362 from a stream bank 680 yards north-west of Marytavy Church. Ventral suture at 14.5 mm., dorsal suture from four septa previous. × 3.2. ? Clymenia Stufe

b. *Platyclymenia* (? *Pleuroclymenia*) sp. Diagrammatic cross-section of the inner whorls based on G.S.M. 87251 from a stream bed north of Manor Hotel, Lydford Station. × 5.2. Platyclymenia Stufe

c. *Sporadoceras posthumum* (Wedekind). Diagram of suture based on G.S.M. 87113–5 from a spoil-heap at South Brentor Quarry. × 0.8. Clymenia Stufe

d. *Imitoceras* cf. *sulcatum* (Münster). Diagram of suture based on G.S.M. 87250 from a stream bed north of Manor Hotel, Lydford Station. × 10. Platyclymenia Stufe

(b) The Marytavy Beds

Locality. Western bank of a stream 680 yards north-west of Marytavy Church (50487919).

A single specimen (G.S.M. 57362), referred to as '*Brancoceras*', was recorded by the Geological Survey (Reid *et al.*, 1912, 8) from this locality. Recent searching has only yielded indeterminable ammonoids.

Imitoceras sulcatum (Münster, 1832, p. 23, pl. 3, fig. 7a–c)

Plate 6, 4, Fig. 1a

Description (of G.S.M. 57362). An incomplete internal mould with a whorl width of 11 mm. at 21 mm. diameter. Involute with closed umbilicus, outline ovate. Growth lines not seen. Constrictions estimated as four in the last whorl, convex. Suture illustrated in the accompanying diagram (Fig. 1a).

Remarks. Dr. Hermann Schmidt of Göttingen has kindly checked the determination of this specimen by means of a plaster cast and photographs. It may be noted that this specimen, and others commonly referred to this species by continental authors, are more comparable with the figures given by Richter (1848, 32, pl. 4, figs. 100–10) than the holographs of Count Münster.

This goniatite represents the only determinable fossil from the Marytavy Beds. In Germany this species ranges from the Cheiloceras Stufe (Wedekind, 1917, 147) possibly up to the Wocklumeria Stufe so that the specimen does not afford precise evidence of age. The horizon is tentatively taken as correlating with the Clymenia Stufe because of the common occurrence of the species at that level in Germany. Clearly further evidence is needed to confirm this.

(c) The South Brentor Beds

Locality. Disused quarries 400 yards north of South Brentor Farm (47978058).

The eastern quarry has provided many ammonoids but most are indeterminable clymenids, crushed flat upon bedding planes. However, limestone nodules occur in the uppermost slate in the north-west corner of the quarry and these have yielded some solid specimens from weathered nodules, especially on old spoil-heaps.

? **Imitoceras** sp. G.S.M. Zi 8324, 8325

Cymaclymenia sp. G.S.M. Zi 8323

Sporadoceras posthumum (Wedekind, 1917, 19, pl. 18, fig. 13, text fig. 47k)

Plate 6, 3, Fig. 1c

Description (of G.S.M. 87113–5, one specimen). A fragmentary internal mould. At a diameter of *c.* 56 mm. the whorl width is 28 mm., the whorl height *c.* 34 mm. and the impressed depth *c.* 15 mm. Shell form involute, umbilicus probably closed, outline rounded and laterally compressed. Growth lines not seen. Suture (Fig. 1c) shows a very small ventral lobe, a pointed second adventitious lobe asymmetrical with sub-parallel sides. The intervening saddle is flat topped or forming only a slight lobe if at all. First adventitious lobe V-shaped and asymmetrical.

Remarks. The suture and shell form of this specimen show close agreement both with the figures of Wedekind and of Schmidt (1922, 328). The saddle adjacent to the ventral lobe may be flatter than on the holotype, but this cannot be ascertained with certainty owing to the poor preservation of the only available specimen. Certainly no prominent third adventitious lobe is formed so the specimen is not a *Discoclymenia*, the genus which is supposed to have arisen from this species.

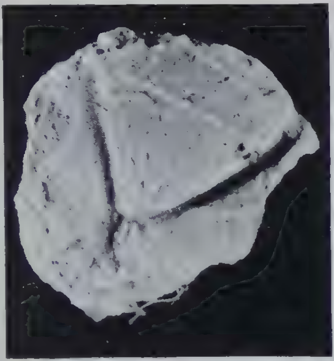
EXPLANATION OF PLATE

1. *Imitoceras* cf. *sulcatum* (Münster). Lateral view of a specimen from a stream bed north of Manor Hotel, Lydford Station, G.S.M. 87250 × 5. Platyclymenia Stufe

2. *Platyclymenia* (? *Pleuroclymenia*) sp. Lateral view of a specimen from a stream bed north of Manor Hotel, Lydford Station, G.S.M. 87251 × 4. Platyclymenia Stufe

3. *Sporadoceras posthumum* (Wedekind). Lateral view of a specimen from a spoil-heap at South Brentor Quarry, G.S.M. 87114 × 1½. Clymenia Stufe. The asterisk marks the second adventitious lobe

4a and b. *Imitoceras sulcatum* (Münster). Lateral and ventral views of a specimen from a stream bank north-west of Marytavy Church, G.S.M. 57362 × 2½. ? Clymenia Stufe



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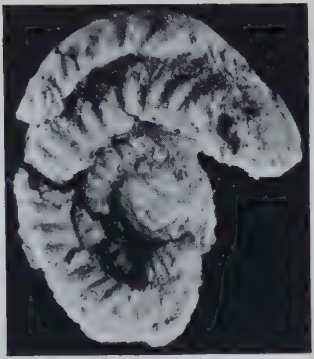

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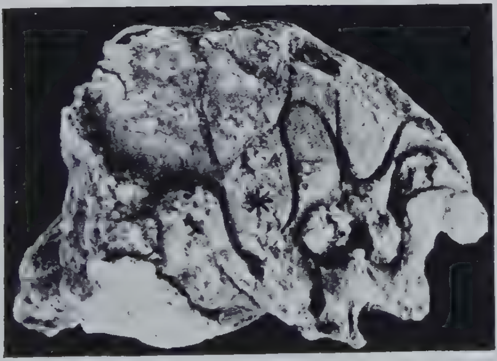

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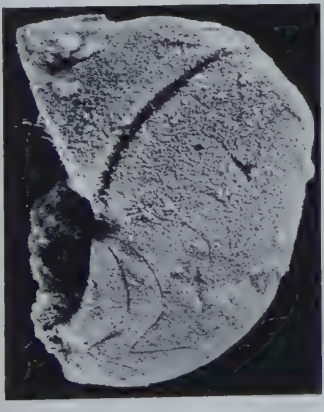

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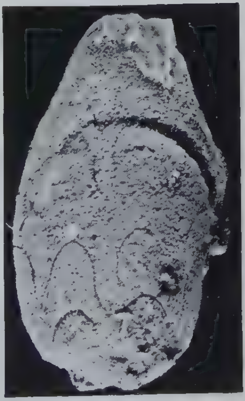

4 b

[*To face p.* 318

These records combine to suggest correlation with the Clymenia Stufe of Germany. The holotype of *S. posthumum* comes from Oberdevon 5a at Hoevel, Germany (Wedekind, 1917, 148). The presence of *Cymaclymenia* supports this correlation.

(d) The North Brentor Beds

Locality. Disused quarry 350 yards north of the South Brentor quarries (47988088).

A loose block found here by Dr. Dearman in March 1956 was found to contain the ammonoids mentioned below. It may be noted that a day's search here by the writer failed to produce further ammonoid material.

Kosmoclymenia sp. cf. **undulata** (Münster) G.S.M. Zi 8329–30

Clymenid indet. G.S.M. Zi 8326–8

During the break-down of this block two very poorly preserved and now disintegrated specimens were noted one of which was thought to be a ? *Sporadoceras* and the other ? *Wocklumeria*. Both these records need confirmation. The evidence gives an Upper Famennian age for the North Brentor Beds for the genus *Kosmoclymenia* is restricted to the Clymenia and Wocklumeria Stufen according to Schindewolf (*in* Moore, 1957, 44). They may correlate with the Wocklumeria Stufe but more material is needed to support this.

3. CORRELATION WITH OTHER AREAS

The ammonoid divisions of the German Upper Devonian are given in the accompanying table together with the new records and the horizons to which they are assigned. The revised nomenclature of Schindewolf (1955) is used.

The levels now identified in the north-west Dartmoor area are also known in the Launceston region, some ten miles farther west, where representatives of the Platyclymenia and Clymenia Stufen were figured by Phillips (1841) and Ansted (1838) and where the Wocklumeria Stufe has recently been identified (House & Selwood, 1957).

Further investigation is needed with regard to the lower horizons of neighbouring areas. At Saltern Cove in Devon the Upper Frasnian is apparently overlain by slates of Cypridenenschiefer facies and in the Padstow area of North Cornwall several hundred feet of Purple and Green Slate of Cypridenenschiefer facies succeed dated Middle Frasnian beds. It is to be presumed, therefore, that the Cypridenenschiefer facies is, in part at least, of Cheiloceras Stufe age (House, 1958). At Launceston in North Cornwall and Chudleigh in South Devon the Platyclymenia Stufe is represented largely by carbonates in the form of limestones, calcareous slate, or 'kramenzelstein'. Whether the Cypridenenschiefer grades upward into this facies, or is in part contemporaneous with it, still remains to be determined.

TABLE I. **Table showing the ammonoid divisions of the German Upper Devonian and succession which has so far been dated in the region north-west of Dartmoor**

LOWER CARBONIFEROUS		Gattendorfia		Not known
UPPER DEVONIAN	FAMENNIAN	Wocklumeria	Oberdevon 6	? North Brentor Beds
		Clymenia	Oberdevon 5	South Brentor Beds and ? Marytavy Beds
		Platyclymenia	Oberdevon 3 and 4	Manor Hotel Beds
		Cheiloceras	Oberdevon 2	Not known
	FRASNIAN	Manticoceras	Oberdevon 1	Not known

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Mr. N. E. Butcher has generously taken the accompanying photographs during the author's absence in America. The Durham colleges in the University of Durham gave a grant towards field expenses whilst collecting in Devon.

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An Interglacial Tufa near Hitchin, Hertfordshire

by M. P. KERNEY

Received 5 December 1958; taken as read 5 June 1959

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ABSTRACT: A Pleistocene tufa or travertine containing a remarkable fauna of non-marine Mollusca with strong Central European affinities is described. Three species are recorded as new to this country, comprising the extinct *Acicula diluviana* Hocker, and forms of *Graciliaria* (*Ruthenica*) and *Laminifera* (*Neniatlanta*), members of the *Clausiliidae* hitherto unknown in North-West Europe. An extinct badger (*Meles*) is also present, together with a small microtine fauna of somewhat archaic type. The stratigraphy of the deposits is described and their relation to the local glacial drifts discussed; the evidence suggests that the tufa belongs within the Hoxnian (Great) Interglacial.

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1. INTRODUCTION

THE DEPOSITS described in this paper lie about one mile WNW. of the town of Hitchin, on the eastern flank of a chalk valley containing the source of the River Oughton. In 1943 a shallow trench for the laying of a water-pipe was cut along Oughtonhead Lane (Fig. 12) and brief descriptions of the section exposed were published soon after by its observer (Wiggs, 1943, 1944). Some non-marine Mollusca collected were identified by the late A. S. Kennard (1943; Wiggs, 1944, 1945); his final list is contained in the last of these papers and includes a number of species extinct in this country, one of which, *Acicula polita* (Hartmann), had not previously been known here, either living or as a fossil. More recently, the writer decided to re-investigate these deposits, to discover, if possible, their stratigraphical relations, and to make a study of their molluscan fauna, which has proved to be of a kind unique in Britain.

2. STRATIGRAPHY

The following details were not obtained from a single section. It was found that in the field to the north of Oughtonhead Lane the ground had

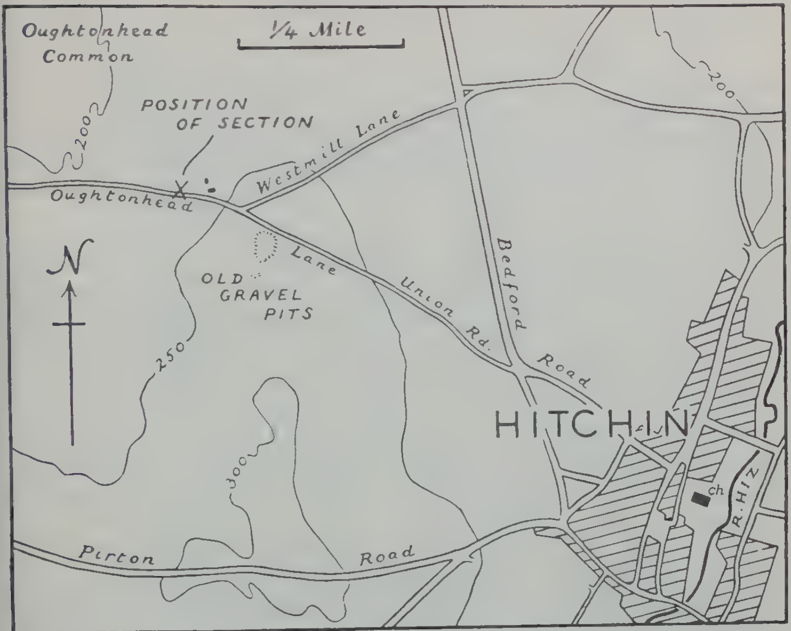


Fig. 12. Sketch-map of the area north-west of Hitchin, to show position of the deposits described

been lowered and the deposits disturbed by what seemed to be old workings, and in that to the south, plough-wash had raised the surface to such an extent that it was not practical to dig a pit. A small trench was therefore cut in the lane itself at the point indicated in Fig. 12 (52/172299) and the information obtained was supplemented by employing a three inch-diameter auger. The use of this tool proved difficult owing to the frequent presence of flints or gravelly seams, and in no place was it possible to reach the top of the Chalk, which appears at a lower level on the lane surface.

DIVISION		ft.	in.
D.	Coarse, extremely ill-graded flint gravel in a matrix of brownish loamy sand, and containing patches of material derived from (C) below. Many glacial erratics, including much Jurassic debris	up to 1	6
	(Unconformity)		
C.	Calcareous tufa or travertine, very variable in texture. A rich fauna of non-marine Mollusca present, indicating a temperate climate	9 in. to 1	3
B.	Light brown highly calcareous sandy clay, or brickearth, with occasional flints and pellets of chalk. A temperate molluscan fauna present, similar to that in (C)	2	0

DIVISION		ft.	in.
A.	A very variable series of alternating fine sandy gravels with glacial erratics, and brown and grey calcareous loams, often almost flintless. No contemporary fossils. This division was mainly proved by augering, but in the dug pit the temperate brickearth (B) was found to rest sharply upon a loamy unsorted flint gravel containing Jurassic material, the top of series (A) ... Estimated at about	10	0
	Chalk.		

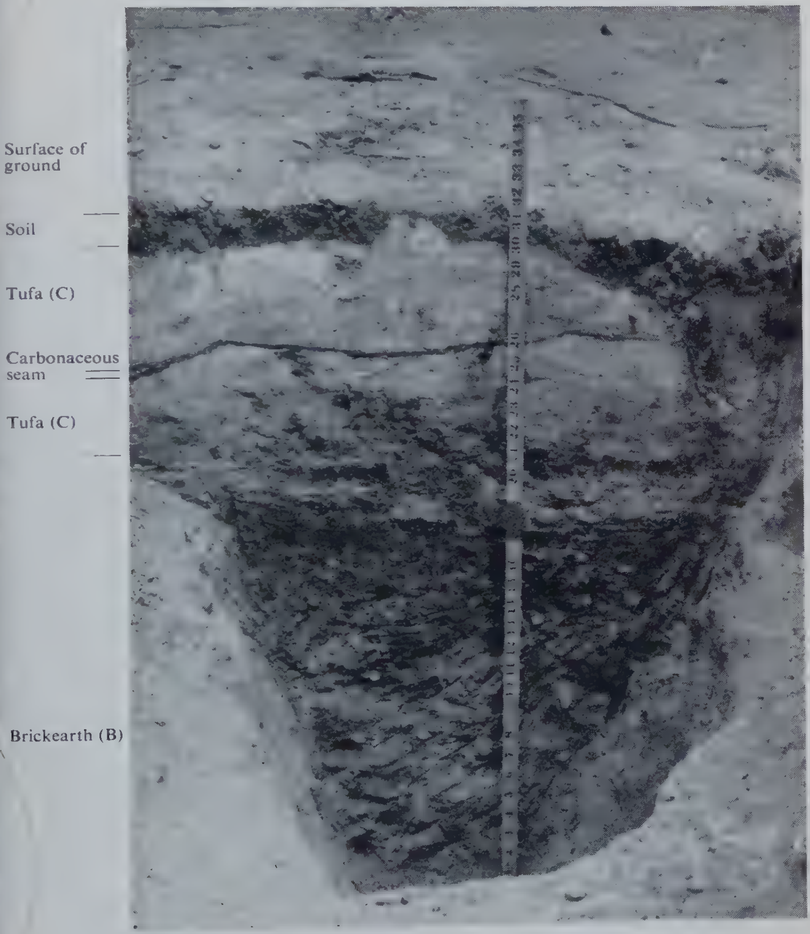
The deposits comprising division (A) are probably of glacial origin and represent outwash from a nearby ice-sheet. The coarser horizons are ungraded or poorly graded and erratics abound, including Jurassic fossils and much vein-quartz. There is an abundance of well-rounded chalk pellets, which are often found embedded in fine-grained calcareous loams containing few or no flints, but these pellets are also present in the gravelly seams. The sands are poorly graded, gritty and sharp; there is no evidence that any of the material is of loessic origin. Large samples of the calcareous loams were washed and examined for contemporary fossils, but none were found.

The form of the Chalk surface below division (A) is unknown. The estimate of ten feet for the thickness of this division is based on the assumption that the top of the Chalk, which is exposed at a lower level on the surface of Oughtonhead Lane, remains more or less horizontal beneath the drift cover as the hill-side rises towards the east, and is probably a minimum value. The greatest amount penetrated with the auger at any one point was five feet three inches.

The relation of this series to the fluvioglacial gravels and other deposits which attain a thickness of some hundreds of feet only one mile to the east in the Hitchin Gap is not clear (Hill, 1908, 1912). It may form part of the western margin of the same drift spread, as the Old Series geological map (46 NE.) suggests; the question must be left unsettled until detailed mapping is carried out in the area.

The brickearth (B) is proved by its molluscan fauna to be a temperate deposit to its base. A small sample taken from the lowermost three inches yielded, among other species, fragments of *Pomatias elegans*, a distinctly southern form and a good indicator of full interglacial conditions. This brickearth is not loessic, either in structure or lithology, and has much the appearance of a normal fluviatile loam deposited from slack water. The fauna is however peculiar in consisting almost entirely of terrestrial species, suggesting that the deposit may in part be a land-wash which accumulated under gentle solifluxion in a temperate climate. The only species present in (B) which has not been found in the overlying tufa is the thermophilous xerophile *Truncatellina cylindrica*.

There is no sharp break between (B) and the tufa (C) above; towards the



Part of section exposed in Oughtonhead Lane, Hitchin, 1957 (TL/172299)
The photograph shows the gradual upward passage and interdigitation between the brickearth (division (B); dark) and the tufa (division (C); light). The latter contains a thin carbonaceous seam. The overlying gravel (D) is not present at this point

top the brickearth becomes whiter and increasingly calcareous and grades into and interdigitates with the tufa (Plate 7). By analogy with comparable deposits elsewhere, the tufa probably accumulated in marshy pools fed by springs, at a time when the climate was sufficiently humid to maintain a constant supply of water, and sufficiently warm to help bring about precipitation of calcium carbonate. The lower part is somewhat marly and frequently rather greyish, while the upper part tends to be granular and powdery, readily breaking into 'crumbs'. Patches are cemented by secondary calcite into extremely hard nodules. The deposit has clearly undergone a good deal of movement since its formation, for the sub-globular shells of the larger helices, particularly *Helix nemoralis*, are often found quite flattened and with their constituent fragments considerably displaced. This can scarcely be due to compaction alone. The disturbance, moreover, took place before re-solution cemented parts of the deposit into nodules, for within these concretions Mollusca broken and 'streaked-out' in an exactly similar manner may be found. Very few shells larger than a few millimetres have escaped crushing.

In one place, there occurred within the tufa a dark carbonaceous seam (Plate 7), a sample of which was examined by Dr. J. W. Franks for possible pollen. He reported that although the material undoubtedly represented vegetable debris, nothing recognisable could be extracted.

The coarse gravel (D) rests unconformably on the tufa, filling pockets and hollows in its surface. It appears to be a melt-water gravel, and consists mainly of sub-angular flints, up to six inches in diameter. It also contains much soft white chalk, pieces of red chalk probably from Lincolnshire, carstone from the Lower Greensand, vein-quartz, and an abundance of Jurassic oysters and belemnites. The junction of this gravel with the tufa is usually sharp, but is sometimes indistinct where much tufaceous material has been incorporated. At the very base, and lying upon the top of (C), was found a flint artifact, a thin ovoid waste-flake in mint condition about three inches long and bearing on one surface accomplished shallow flaking. On typological grounds, this artifact might be assigned to many cultures between the Levalloisian and the Bronze Age, and it therefore does not serve accurately to date the deposit in which it was found.

This gravel may be the same as that formerly worked in the now overgrown pits on the rising ground 300 yards to the south-east (see Fig. 12) and William Hill refers to a section near here showing twenty-five feet of glacial gravel consisting 'chiefly of subangular and rounded flints with a large proportion of chalk-pebbles, together with Jurassic and Carboniferous limestones, ironstone, pebbles of quartz and quartzite, and red chalk' (1908, 20).

The deposits described above outcrop in turn at the surface, being cut off by the present slope of the ground; this fact suggests that they were formed at a time when the shallow chalk valley to the north-west, in which rise the springs supplying the River Oughton, either did not exist or had not retreated to its present position.

3. FAUNA

(a) Mammalia

The following remains of small vertebrates were recovered from the horizon of the tufa (C). They were identified by Mr. J. N. Carreck, who very kindly supplied the notes incorporated below. In addition, a large indeterminate fragment of bone was found in the brickearth (B).

Meles sp. Left m^1; left pm^4 (carnassial). These teeth were not obtained by the writer, but were collected by Wiggs in 1943 (1945, 5). They were later recorded as '*Meles taxus* Boddaert' (= *Meles meles* (Linné)) (Oakley, 1947, 244). They do not compare well, however, with those of the recent British badger and appear to represent an extinct species. There are certain differences in the details of the cusping, and the molar tooth particularly is larger and relatively longer than the corresponding tooth in any living Western European race of *Meles*. This specimen has been presented by Mr. Wiggs to the British Museum (Natural History) (M.18948).

Meles is not otherwise known in this country, prior to the Postglacial, outside Late Pleistocene cave deposits, in which it is almost ubiquitous.

Clethrionomys sp., *glareolus* group. Right m^3 and immature left m^1. This form is probably that recorded, but not named, by Hinton from the Upper Freshwater Bed at West Runton (Cromerian), from the Boyn Hill Terrace deposits at Ingress Vale, Swanscombe, and from the Grays Thurrock Brickearths (Hinton, 1926, 216). It is also known from the Middle Gravels of Barnfield Pit, Swanscombe. On the Continent, this same form occurs associated with faunas of Cromerian and later Pleistocene type in Transylvania, Hungary and South Germany.

Pitmys cf. *arvaloides* Hinton. Anterior portion of right m_1. This is not typical *P. arvaloides* and is certainly not *P. gregaloides* Hinton. There are no other described species of *Pitymys* in Britain, but there may be one or more undescribed forms here. In this country, *P. arvaloides* occurs only in the Upper Freshwater Bed at West Runton and in the Lower Gravel of Barnfield Pit, Swanscombe (New record, recently collected).

Apodemus sp. Perfect right m_1, of the milk dentition. Remains of such a form are known from the Upper Freshwater Bed at West Runton, from Ingress Vale, Swanscombe, and from the Grays Thurrock Brickearths.

As regards the age of this assemblage, Mr. Carreck considers the presence of the peculiar *Clethrionomys* and particularly of *Pitymys* cf. *arvaloides* to indicate a date not later than the Saale (Gipping) Glaciation.

(b) Non-marine Mollusca

Non-marine Mollusca were present in the tufa (C) and in the underlying brickearth (B). The following fauna was obtained by washing bulk samples from both these horizons, although the tufa proved far more prolific and much larger quantities were examined. A study of the fauna was rendered difficult by the very fragmentary nature of nearly all the material. This poor preservation affects the frequencies given in the list below; for various species differ greatly in their resistance to crushing, and while fragments of some are readily identified those of others are not. The numbers given for the species of *Clausiliidae* and *Zonitidae* particularly are gross underestimations and reflect but faintly the abundance of undeterminable fragmentary material of these families in the samples washed. In all cases, the numbers are minimum figures, precautions being taken, such as counting apices or lip fragments only, to avoid listing as separate individuals pieces of the same shell.

	Division	
LIST OF MOLLUSCA	(B) Brickearth	(C) Tufa
* *Valvata piscinalis* (Müller)	—	3
* *Bithynia tentaculata* (Linné)	—	1
Pomatias elegans (Müller)	5	15
†*Acicula* (*Platyla*) *polita* (Hartmann)	1	101
†*Acicula* (*Hyalacme*) *diluviana* Hocker	—	58
Carychium tridentatum (Risso)	5	154
* *Lymnaea truncatula* (Müller)	1	23
* *Aplexa hypnorum* (Linné)	—	2
* *Planorbis leucostoma* Millet	—	76
* *Planorbis crista* (Linné)	—	3
Azeca goodalli menkeana (C. Pfeiffer)	5	235
Cochlicopa lubricella (Porro)	1	2
Truncatellina cylindrica (Férussac)	1	—
Vertigo pusilla Müller	—	1
Vertigo pygmaea (Draparnaud)	—	5
Vertigo angustior Jeffreys	—	1
Lauria anglica (Wood)	—	23
Acanthinula aculeata (Müller)	1	26
Vallonia costata (Müller)	3	9
Ena montana (Draparnaud)	4	3
Marpessa laminata (Montagu)	—	24
Clausilia bidentata (Ström)	—	15
†*Clausilia* cf. *pumila* C. Pfeiffer	—	18
†*Clausilia ventricosa* Draparnaud	—	5
'*Clausilia*' spp.	25	Ab.
†*Laminifera* (*Neniatlanta*) aff. *pauli* (Mabille)	—	10
†*Graciliaria* (*Ruthenica*) *filograna* (Rossmässler)	—	34
Balea perversa (Linné)	—	4
Helicodonta obvoluta (Müller)	3	51
Helicigona lapicida (Linné)	2	14
Arianta arbustorum (Linné)	—	12

LIST OF MOLLUSCA	Division (B) Brickearth	Division (C) Tufa
Helix nemoralis Linné	9	Ab.
Hygromia hispida (Linné)	—	6
Punctum pygmaeum (Draparnaud)	—	8
†*Discus ruderatus* (Férussac)	1	1
Discus rotundatus (Müller)	12	272
Euconulus fulvus (Müller)	—	1
Vitrea contracta (Westerlund)	—	13
Oxychilus cellarius (Müller)	2	72
Retinella radiatula (Alder)	3	10
Retinella pura (Alder)	—	4
Retinella cf. *nitidula* (Draparnaud)	—	2
Zonitoides excavatus (Alder)	4	6
†*Vitrina* (*Semilimax*) cf. *semilimax* Férussac ...	—	5
'*Limax*' spp.	23	Ab.
**Pisidium casertanum* (Poli)	—	7

* Freshwater forms
† Species extinct in Britain

The fauna of the tufa consists mainly of land snails, but seven freshwater forms are also present. Five of these (*Lymnaea truncatula*, *Aplexa hypnorum*, *Planorbis leucostoma*, *P. crista* and *Pisidium casertanum*), comprising 111 shells, do not require more than a bare minimum of water and can often be found living in places that are little more than marshy hollows. In such places, the distinction between freshwater and land molluscs becomes blurred, and the hygrophiles *Lauria anglica* and *Vertigo angustior* may have lived in the same environment. In addition, Kennard records *Succinea* sp. Such species prove that the tufa formed on marshy ground, as its lithology suggests.

Valvata piscinalis and *Bithynia tentaculata* are not however compatible with such a habitat, for these two operculates usually need a fair body of water, preferably flowing, and which is not liable to dry up at intervals; they are characteristically 'river' species. The former is represented by a worn operculum only, which suggests derivation from an earlier deposit, but the three examples of *V. piscinalis* do not look derived and probably reflect the presence of more permanent water somewhere near.

The land Mollusca indicate a highly calcareous area covered with deciduous woodland or thick scrub, somewhat similar ecologically to an old self-sown wood of ash or beech on chalk or limestone in southern England at the present day, but probably with more uncleared ground-litter than most and thus maintained more evenly damp. Woodland is suggested by the presence of such forms as *Acicula polita*, *Ena montana* and *Helicodonta obvoluta*, and by the extraordinary abundance of various *Clausiliidae*. *Azeca goodalli menkeana*, a species requiring shade and cover, occurs in remarkable profusion. There is no evidence of much open ground;

grassland forms and xerophiles are virtually absent, and Kennard's record of *Pupilla muscorum* (*in* Wiggs, 1945, 5) is an error. The possible exception to this statement is *Vallonia costata*, which generally favours rather dry open situations, but which may, on occasions, also be found living in marshes.

The occurrence of *Zonitoides excavatus* is somewhat unexpected, for this species is at the present day calcifuge in habit and would scarcely be looked for in association with such an obligatory calcicole as *Pomatias elegans*. Boycott, however, found by experiment that it would live and breed when kept on calcareous soil along with *P. elegans* (Boycott, 1934, 29), and *Z. excavatus* is now known from a sufficiently large number of highly calcareous Quaternary deposits to make it appear probable that some change or restriction of habitat has taken place.

The climate was fully temperate and possibly with summers warmer than those of south-east England today, certainly no cooler. The combination of deciduous woodland and marsh faunas is not easily explained, although it is one characteristic of many warm Postglacial (Atlantic) deposits in this country. Since there seems no obvious way by which the Mollusca can have been transported far after death, the swampy pools in which the tufa was precipitated must have been closely surrounded by trees and scrub. It would be hard to find an analogy to these conditions in Britain at the present time.

The great interest of the Hitchin fauna lies in the presence of genera and species whose occurrence in this country, or even in north-west Europe, had not been suspected. This fact reflects clearly the imperfection of the geological record and the inadequacies of our knowledge, even in so familiar a field. Most of the information on British interglacial Mollusca has hitherto been derived from a study of fluviatile or lacustrine sediments in which land snails are often scarce and are generally restricted to marsh or grassland forms; these lived on or near the water's edge and were incorporated by chance flooding. But the Hitchin tufa, the first of interglacial age yet investigated in Britain, gives us the fauna of a calcareous woodland, a habitat of which virtually nothing was known.

4. NOTES ON CERTAIN SPECIES OF MOLLUSCA

Pomatias elegans. Though common in many warm Postglacial sediments, this southern species is almost unknown in the English Pleistocene. It has recently been recorded from the middle of the Last Interglacial (Zone F of the Eemian) at Bobbitshole, Suffolk (Davis, 1955; Sparks, 1957, 39).

Acicula polita (Figs. 1, 1a, 4). No species of *Acicula* is elsewhere known from undoubted interglacial deposits in Britain. The presence in the Oughtonhead Lane tufa of *A. polita*, a widespread form today in France and Central Europe, was noted by Kennard in 1945 (*in* Wiggs). Although common, no complete shells have been recovered, but all the fragments compare exactly with recent *A. polita* from Pomerania and North Bavaria, kindly lent by Dr. H. Schlesch.

Acicula diluviana (Figs. 2, 2a, 3). This apparently extinct species was first described (but not figured) from specimens found in an interglacial tufa at Brüheim in Thuringia (Hocker, 1907, 92–3). In general shape, it resembles *Acicula fusca* (Montagu) (Figs. 5, 5a), the only member of the genus found in Britain in the Postglacial and at the present day, but differs from it in the following characters:

The shell is somewhat larger and more elongate and the whorls slightly taller in proportion to their breadth. The aperture is more pear-shaped and its margin bears a fairly distinct callus. There is no umbilicus. Viewed laterally, the upper part of the outer margin of the aperture near the point of contact with the preceding whorl exhibits a minute re-entrant indentation or sinulus, not present in *A. fusca* (cf. Figs. 2a and 5a). Lastly, the surface of the shell is quite smooth and polished and entirely destitute of the sharply cut vertical striae which are so distinctive a feature of *A. fusca*.

Average length of five complete examples from Hitchin: 2.8 mm.; average breadth: 1 mm.

Juveniles or broken apices of *A. diluviana* may be distinguished from those of associated *A. polita* by their narrower form (cf. Figs. 3 and 4) and by their lack of brown pigment, which in the latter species generally survives in the fossil.

Through the kindness of Dr. A. Zilch, the writer has been able to examine seven syntypes of *A. diluviana* collected by Hocker at Brüheim, and preserved in the Senckenberg Museum at Frankfurt (Reg. No. 32559), and with these the Hitchin shells agree perfectly. Brüheim remained the only known locality for this species until a few years ago, when Dr. R. Dehm discovered it in some extensive Pleistocene tufas at Schmiechen, about thirteen miles WSW. of Ulm, Bavaria, and which he considers to belong to the Mindel–Riss Interglacial (Dehm, 1951, pp. 263–5, pl. 17, figs. 19–21). Examples from Schmiechen lent by Dr. Schlesch proved exactly similar to the Brüheim shells in all respects. The only difference that is detectable between *A. diluviana* from both these German sites and the shells from Hitchin is that the latter tend, on average, to be a little longer. Hocker's original diagnosis gives length as 2.6 mm., while Dehm quotes a range of 2.55 mm. to 2.70 mm. for Schmiechen material.

An *Acicula* very close to *A. diluviana* is also known from a calcareous Pleistocene scree deposit at Stránská Skála, near Brno, Czechoslovakia. The associated microtines include Early Pleistocene (Cromerian) species of *Pitymys* and *Mimomys* and the deposit is assigned on these grounds to the Gunz–Mindel Interglacial (Ložek and Fejfar, 1957). Specimens of the

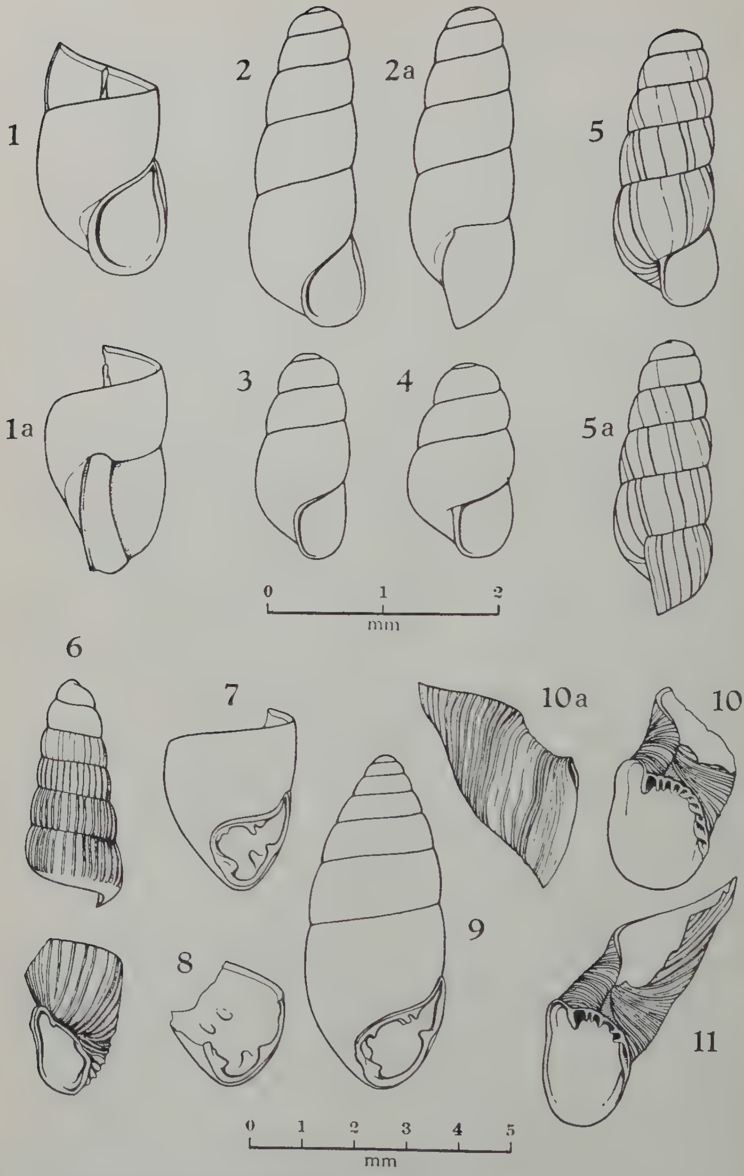
Acicula sent by Dr. Ložek greatly resemble those of *A. diluviana* from Britain and Germany, but show certain slight differences in the shape of the apical whorls, suggesting that these shells may belong to a distinct geographical race, or, if they are of greater age, as the evidence suggests, to a chronological subspecies. The first two or three whorls tend to be very slightly more tumid and the intervening sutures consequently deeper, but these differences are so small that the Czech material is almost certainly correctly referred to *A. diluviana*.

Being extinct, nothing can be known directly of the ecology of *Acicula diluviana*, but like other members of the genus it was probably a shade-loving form favouring woodland. Its association with highly calcareous deposits suggests that it was a calciphile, unlike the recent British *A. fusca*, which is practically indifferent to the presence or absence of lime (Boycott, 1934, 33).

Azeca goodalli menkeana (Figs. 7, 8). *Azeca goodalli* (Férussac) has been recorded from a number of Great and Last Interglacial deposits in England, but in all cases where specimens have been examined they are found to differ considerably from recent British examples of that species. The shells are slightly but consistently smaller and possess a larger number of denticles on the inner palatal wall of the aperture: viz. a large marginal tooth, a similar large tooth a little further within the aperture, and two much more deeply seated and smaller sub-parallel denticles, usually seen clearly only by breaking away the shell wall (Fig. 8). Of these four teeth, only the first is normally present in modern British *Azeca*.

A form closely similar to these Pleistocene shells still lives at the present day in France, Denmark and Germany, where it is known under the name of *Azeca menkeana* (C. Pfeiffer) (Ehrmann, 1933, p. 33, pl. 1, figs. 4, 4a). The existence of two distinct European forms was pointed out by Pilsbry (1908), and a few authors, notably Germain (1930, 453–4), have tentatively given them specific rank. Mr. Hugh Watson has suggested to me that they are perhaps best regarded as geographical races, or true subspecies, *Azeca goodalli sensu stricto* having a western distribution (Britain, West France, North-East Spain), and *A. goodalli menkeana* living farther to the east (France, Central Europe). Occasional intermediates are known and some may indicate local hybridisation in regions where overlap occurs, such as is known to take place in the *Arion ater* aggregate (Cain & Williamson, 1958). Comparative anatomical studies have not yet been carried out. True *Azeca goodalli* is apparently not found in the Pleistocene, either here or on the Continent.

Lauria anglica. In contrast to the general composition of the Hitchin fauna, this species has a markedly western range, being practically endemic to Britain and Ireland. It has not hitherto been reliably recorded prior to the Postglacial.



Figs. 1–11. British *Acicula*, *Azeca*, *Graciliaria* and *Laminifera*

Clausilia cf. *pumila* and *Clausilia ventricosa*. Both are Central European species which occur in a number of Great and Last Interglacial deposits in England. In addition, Kennard records from Oughtonhead Lane *Clausilia cruciata* Studer, a Continental form closely allied to *C. pumila* (*in* Wiggs, 1945). Due partly to the very broken nature of the Hitchin *Clausiliidae*, it is not possible to be certain whether or not *C. cruciata* is represented, despite comparison with recent examples of that species. The specimens from this site in the Kennard Collection in the British Museum (Nat. Hist.), and labelled by him '*C. cruciata*', prove in fact to be all apertural fragments of *Graciliaria filograna* (see below).

Laminifera aff. *pauli* (Figs. 10, 10a, 11). This aberrant genus of the *Clausiliidae* is only known living at the present day in a few places in the French and Spanish Pyrenees, where it is represented by two rather distantly related species: *Laminifera* (*Neniatlanta*) *pauli* (Mabille) and *L.* (*Bofilliella*) *subarcuata* Bofill. The Hitchin material is unfortunately badly broken. Ten apertural fragments were recovered. They exhibit a surprising degree of variation among themselves in the quality of the vertical ribbing and striation on the last whorl, in the amount of projection of the detached portion of this whorl from the axis of the fusiform shell, in the breadth of the aperture, and in the number of folds or lamellae present in its upper part (cf. Figs. 10 and 11), but indicate a species which is certainly closely related to the living *L. pauli*. Good photographs of this form are given by Germain (1930, pl. 13, figs. 389–90). Compared with these fragments, the recent specimens of *L. pauli* that it was possible to examine showed much slighter variation, and differed mainly in possessing fewer, rather weaker and less conspicuous apertural folds, the number of which was about six to eight, compared with from seven to eleven in the fossils. It is difficult to say what weight should be given to these differences and they may in part be due to the highly calcareous environment in which the Hitchin Mollusca lived. It would be desirable to examine much larger series of shells to determine the range of variation and its possible significance. The Hitchin *Laminifera* may prove to belong to a distinct species or subspecies, particularly in view of its geographical and chronological isolation, but in default of better material it has been thought wisest to record it as *Laminifera* aff. *pauli*. Judging from published figures, none of the Tertiary fossil forms are very closely related.

A few Clausiliid apices were found which possibly belong to the same species: they exhibit a curiously flattened whorl profile coupled with an almost obsolete suture, features seen in the apical whorls of *L. pauli*.

The *Laminiferinae* were of much greater importance in the Earlier Tertiary, being well represented in the Palaeocene, Eocene, Oligocene and Lower Miocene of France, Italy, Germany and Bohemia; two isolated species are also known from the Upper Pliocene (Astian) of North Italy

(Wenz, 1923, 794–801).[1] The unexpected presence of a form of *Laminifera* in the Pleistocene of England throws interesting light on problems of faunal migration. The geological history of the genus suggests that during the Newer Tertiary and the Quaternary gradual extinction overcame *Laminifera* and its allies in Central Europe, perhaps as a result of competition in that area from more advanced and later evolved *Clausiliidae*, but that a few forms were able to survive, at least for a time, in widely separated localities near the limits of the geographical distribution of the family.

Graciliaria (*Ruthenica*) *filograna* (Fig. 6). First record for Britain; a local though widely distributed Central and Eastern European species. Recent examples from Thuringia, Bavaria and Czechoslovakia proved identical with the fragments from Hitchin. No complete shells were found, but the apex of *G. filograna* has a very distinctive form, better seen than described in words, and which is not likely to be mistaken for that of any other European Clausiliid. The rate of increase of the whorls is at first very rapid, and then, after about one and a half to two turns, it diminishes rather abruptly, producing a characteristic pointed conical apex with an apical angle of about 60° (Fig. 6). *G. filograna* is a small Clausiliid, rarely exceeding 9 mm. in length. Its sculpture is also distinctive; the shell bears regular vertical ribs, which, in relation to its size, are stronger and sharper than in most other European members of the family.

Graciliaria filograna frequents woods and scrubby places on calcareous soil in East, Central and South Germany, Czechoslovakia, the North-West Balkans, the Carpathians, Poland, Lithuania, Estonia and European Russia (Ehrmann, 1933; Ložek, 1956). The species undoubtedly at one time had a wider distribution. Judging from specimens seen, it occurs in some abundance in Pleistocene scree breccias at Menton on the Italo–French Riviera, from which it has been recorded as a new species under the name of *Clausilia paulucciana* (Nevill, 1880, p. 132, pl. 14, figs. 1, 1a).

Discus ruderatus. Extinct in Britain but common in several interglacial and warm Early Postglacial (Boreal-Atlantic) deposits.

Vitrina cf. *semilimax*. *V. semilimax* has at the present day an Alpine and Central European range. The degenerate shells of the *Vitrinidae* are difficult to name with certainty but the five examples from Hitchin compare closely with this species. Similar shells are also known from the Upper Freshwater Bed at West Runton (Cromerian) and from Swanscombe (Great Interglacial). *V. semilimax* is recorded by Dehm from the Schmiechen tufas (1951, 245).

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[1] Judging from the published figures and descriptions, some at least of the imperfectly preserved casts of *Clausiliidae* from the Bembridge Limestone (Lower Oligocene) of the Isle of Wight, described as *Clausilia striatula*, may prove to belong to a *Laminifera* (Edwards, 1852, pp. 79–80, pl. 11, figs. 6a–h).

5. AGE OF THE DEPOSITS AND CONCLUSIONS

The deposits which form the subject of this paper cannot pre-date the earliest major glaciation of the South Midlands, for their lowermost member, division (A), contains abundant erratic material, including some far-travelled constituents. Not more than two distinct tills have so far been recognised around Hitchin, produced during the Lowestoft and the Gipping ice-advances of Baden-Powell, the former of which is now generally assigned to some phase of the Elster (Mindel) Glaciation (West & Donner, 1956). Apart from the disputed Chiltern Drift (Wooldridge, 1938, 645–7), which lies at considerably higher elevations to the south-west, there is no evidence for an earlier major ice-sheet in this area.

Since the overlying gravel (D) appears also to be of glacial origin, the horizons (B) and (C), with their fully temperate molluscan fauna, may fairly be claimed as interglacial. Furthermore, much of the crushing from which the tufa suffers is probably the result of glacial disturbance. In the original trench section, the tufa was observed to be thrown into gentle folds and, in one place, to be faulted (Wiggs, 1943). These disturbances may have occurred at the time of the Gipping ice-advance or during some subsequent cold period, but since the Gipping Glaciation left abundant local traces, whereas no till belonging to any phase of the Last Glaciation has been recognised so far south, the former alternative is slightly the more probable.

A little further help is given us by the fauna. Regarding the vertebrates, Mr. Carreck states that the assemblage cannot be later than the Saale (Gipping) Glaciation. The molluscan fauna is less easily interpreted, for there is nothing known in this country to which it can be compared. On the Continent, the Pleistocene tufas at Schmiechen in Bavaria mentioned earlier provide the closest faunal parallel at present available (Dehm, 1951). Unfortunately, in the case of these deposits there does not appear to be any direct stratigraphical evidence of age, although Dr. Dehm considers that they probably belong within the Mindel–Riss Interglacial. The extinct species *Acicula diluviana* is not known to have survived to a later period.

Summing up, purely geological evidence suggests that the temperate horizons (B) and (C) are almost undoubtedly later than the Lowestoft Glaciation, outwash of which may be represented by division (A), and, less certainly, earlier than the Gipping ice-advance. If this be correct, the tufa belongs within the Hoxnian Interglacial of West (1956), which on cultural and other grounds is generally correlated with the Mindel–Riss, or Great Interglacial of Continental workers. The evidence provided by the microtines and by the Mollusca lends support to this dating, and shows furthermore that only a short period near the climatic optimum of the interglacial can be represented. Lacustrine deposits of the same interglacial, yielding mammalian remains, plants and a flint industry of Middle Acheulian type, have long been known from the floor of the Hitchin Gap (Reid, 1897), where they rest on boulder clay and a great thickness of gravels presumably associated with the Lowestoft Glaciation.

ACKNOWLEDGMENTS

I owe a special debt of gratitude to the late Hugh Watson, who gave me the benefit of his wide knowledge of Mollusca in much helpful discussion. Mr. J. N. Carreck kindly reported on the vertebrate remains. Mr. R. J. Wiggs first introduced me to the site and helped with the field-work, and the writer also received assistance from Mr. F. Berry, Mr. C. P. Castell, the late A. G. Davis, Dr. R. Dehm, Mr. P. Fookes, Dr. J. W. Franks, Mr. B. W. Sparks and Dr. R. G. West. Continental material was sent by Dr. V. Ložek (Prague), Dr. Hans Schlesch (Denmark) and Dr. A. Zilch (Frankfurt-am-Main).

EXPLANATION OF FIGS. 1–11

Unless otherwise stated, all specimens are from Pleistocene tufa (division C), Oughtonhead Lane, Hitchin, Hertfordshire.

Figs. 1, 1a. *Acicula* (*Platyla*) *polita* (Hartmann). Fragment. 1, frontal view; 1a, lateral view

Figs. 2, 2a. *Acicula* (*Hyalacme*) *diluviana* Hocker. 2, frontal view; 2a, lateral view

Fig. 3. *Acicula diluviana*. Juvenile

Fig. 4. *Acicula polita*. Juvenile

Figs. 5, 5a. *Acicula* (*Acicula*) *fusca* (Montagu). Recent, Shoreham, Kent. 5, frontal view; 5a, lateral view

Fig. 6. *Graciliaria* (*Ruthenica*) *filograna* (Rossmässler). Fragments of two specimens juxtaposed to show proportions of complete shell

Fig. 7. *Azeca goodalli menkeana* (C. Pfeiffer). Fragment

Fig. 8. *Azeca goodalli menkeana*. Fragment of last whorl, showing deep-seated palatal denticles

Fig. 9. *Azeca goodalli* (Férussac). Holocene (Atlantic), Tilekiln Green, Takeley, Essex

Figs. 10, 10a. *Laminifera* (*Neniatlanta*) aff. *pauli* (Mabille). Fragment of last whorl. 10, frontal view of aperture; 10a, lateral view

Fig. 11. *Laminifera* aff. *pauli*. Fragment of last whorl of another specimen

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Easter Field Meeting in North-West Dartmoor

26–30 March 1959

Report by the Directors: W. R. DEARMAN and N. E. BUTCHER

Received 11 May 1959

THE OBJECT of the meeting was to demonstrate recent work (Dearman & Butcher, 1959) on the stratigraphy, structure and petrology of the Upper Devonian and Carboniferous sediments and associated igneous rocks along the north-west margin of the Dartmoor granite. The party of eighteen members assembled in Okehampton on the evening of 26 March, when the Directors gave a brief outline of the geology of the area and the programme to be followed during the next four days. The Association had previously visited part of the area in 1922 (Sherlock, 1923).

Friday, 27 March

Director: W. R. DEARMAN

Okehampton and Meldon. The day was devoted to the examination of the Upper Culm Measures in the neighbourhood of Okehampton and the inlier of the Lower Culm Measures at Meldon. The party drove first to Knowle Quarry (594962)[1] where the symmetrical folds in the unaltered Upper Culm Measures were contrasted with the overfolds in the neighbouring Okehampton Brickworks Quarry (594961). Returning to Okehampton the roadside exposures in the Upper Culm along New Road (586948 to 583943) were examined. The party rejoined the bus and drove to the British Railways Quarries (567926) at Meldon. Here in the 860 North Bay the typical faulted zig-zag overfolds of the Lower Culm Measures inlier were well displayed. Particular attention was paid to the metasomatic development of coarse-grained calc-silicate hornfels from the black radiolarian cherts which occur near the top of the Lower Culm succession. The party walked southwards to the disused face opposite the crushing plant to see the faulted inlier of the Slate-with-Lenticles Group. The full sequence of the Lower Culm, with two basic dykes, was exposed in the adjoining 860 South Bay. After lunch the party walked up the incline road to the 950 Waste Tip, and from this vantage point the Director pointed out the relationship between the geology and the topography as far south as the granite of Yes Tor. A short walk along the 950 South Cutting brought the party to an exposure of deeply weathered limestones and cherts. The Meldon Aplite Quarries (567920) were next visited, and the traverse of the inlier was completed by walking up the valley of the Red-a-ven Brook to the disused Red-a-ven Mine (570917).

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[1] All National Grid reference numbers occur within the 100 km. square 20 (SX).

Saturday, 28 March

Director: W. R. DEARMAN

Belstone and Sticklepath. The day was spent in a further examination of the Lower and Upper Culm Measures along the northern border of Dartmoor. The party left Okehampton by the footpath leading to Ball Hill (598947) and Fatherford Viaduct (603597), examining small exposures of the Upper Culm sandstones and shales on the way. The East Okement River was crossed by the footbridge just upstream from the viaduct, and by following the footpath on the west bank of the river to Chapel Ford (608934) a traverse was made from the northern normal limb of the Lower Culm anticlinal inlier, across the core of the Slate-with-Lenticles Group, into the steep beds of the southern limb of the anticline. Some members of the party continued upstream on the eastern bank to complete the traverse to the Upper Culm, and then climbed Watchet Hill (615930) to reach Belstone (619935) for lunch. The rest of the party followed the footpath northwards to the hilltop above West Cleave (609941) for the view north across the Permian of the Crediton Valley to Exmoor, then joined the road and walked to Belstone. After lunch the party walked south-westwards across the heather-covered outcrop of the Upper Culm Measures of Watchet Hill to the granite tors of Belstone Common. Below in the valley of the Taw River lay the great waste of Taw Marsh (620910); recent borings for water have revealed that beneath the marsh there is over one hundred feet of granite detritus resting on solid granite. Returning to Belstone the party took the path along the disused leat leading to Skaigh (631939) on the northern slopes of Belstone Cleave, passing crags of tuff and agglomerate of the Volcanic Group of the Lower Culm Measures. The disused workings of Ivy Tor Mine (627934) could be seen on the southern bank of the Taw River, and the Director pointed out that this marked the southern margin of the Lower Culm inlier which had also been mined farther east at Ford (643935). The dumps of the disused Belstone Consols (Mid-Devon) Mine (632945), at the northern margin of the Lower Culm inlier, were visited next. The party then walked from the mine to the end of the lane (637942) high on the hill above Sticklepath. There was a clear view from here across the Sticklepath Fault Zone along which the Belstone Consols lodes have been displaced over one mile south-east to the disused Ramsley Mine (650930). The party followed the steep path down into Sticklepath and walked along the main road to Ramsley. Brecciated granite in a sand-pit (649928) near Fulford, directly opposite the mine dumps, again clearly indicated the magnitude of the offset along the Sticklepath Fault. The bus was waiting to take the party to the disused South Tawton Limestone Quarries, where the day's work ended with a fruitless search for fossils in the easily accessible exposures in the most northerly of the quarries (658951).

Sunday, 29 March

Director: N. E. BUTCHER

Brentor and Lydford. The day was mainly devoted to an examination of the Brentor and Lydford inliers of the Transition Series within the Culm Measures outcrop. The party drove first to Brent Tor (471804) from the summit of which low cloud unfortunately allowed only a restricted view of the north-western slopes of Dartmoor. The crags of pyroclastic rocks were examined on descending the tor. In the nearby South Brentor quarries (480806) the Upper Devonian *Clymenia* Zone beds were seen, lamellibranchs and ostracods being collected. The party then walked on to a quarry (480809) near North Brentor in green slaty beds of ? *Wocklumeria* Zone age. The coach was rejoined in North Brentor and the party drove to the Manor Hotel near Lydford Station where a nearby stream bank locality (502832) in *Platyclymenia* Zone slates was visited. After lunch Lydford Gorge was entered at its lower end at the elbow of river capture (Dewey, 1916), the geomorphological features exciting much discussion. The River Lyd Slate-with-Lenticles Group was examined in passing through the gorge, at the upper end of which most members visited the Devil's Cauldron. Continuous rain and a walk along a swinging plank which was awash due to the high-water level made the visit to this large pot-hole in the depths of the gorge a memorable experience. Leaving the gorge the party visited a quarry (515854) at Lydford in contact-altered calcareous siltstones of the Transition Series and then briefly compared and contrasted them with calc-flintas of the Lower Culm Watervale Calcareous Group in stream exposures by the main road (518839) near Watervale. The day's work ended with a walk up the valley of the River Lyd from the main road towards the granite, examining the lithology and deformation structures of the River Lyd Group within the metamorphic aureole of the granite. Finally some members of the party visited a quarry (533864) in the Upper Culm Measures close to the granite near Nodden Gate.

Monday, 30 March

Director: N. E. BUTCHER

Marytavy and Tavistock. The main object of the day's programme was to examine the Lower and Upper Culm Measures, comparing and contrasting the rocks with those seen in the northern part of the area on the first two days. The party travelled from Okehampton along the main road towards Tavistock, features of geological interest being pointed out on the way. The first stop was at Wheal Betsy (510810) where the mine dumps were briefly searched for galena before the party proceeded to examine the nearby stream section in the Upper Culm Measures. Cast structures on the bottoms of the inverted sandstones of this Black Down Group particularly attracted attention. Wheal Friendship at Marytavy was next visited where the Director gave an account of the operations of this large disused copper-mine. The party then examined the nearby Famennian inlier (505792), of ? *Clymenia* Zone age. The coach was rejoined and a brief stop made outside Pitts Cleave Quarry (501761), the Director giving an account of the igneous rock types—oligoclase-dolerites, hornblende-dolerites and trachytes—to be found as sills in the quarry. The party proceeded to Wilminstone Quarry (490755) to examine the hinge of a recumbent fold in which occurs a 200-foot thick sill of dolerite. After lunch in Tavistock the top of the inverted Lower Culm Measures succession was studied in Lower Deerpark Quarry (483743) and adjacent exposures. The Whitchurch Down Greywacke Group, the southernmost outcrop of the Upper Culm Measures in the area, was examined in the River Tavy exposures immediately north of the footbridge (479741). The Director demonstrated the facies differences between these rocks and the Upper Culm Measures to the north. The party then drove over Whitchurch Down, visiting a quarry (512739) in the Upper Devonian Slate Series which crops out to the south of the Culm Measures. After Dr. G. W. Himus had proposed a vote of thanks to the Directors, the party returned to Okehampton by way of Tavistock.

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Dewey, H. 1916. On the Origin of some River-Gorges in Cornwall and Devon. *Quart. J. geol. Soc. Lond.*, **72**, 63–76.

Sherlock, R. L. 1923. Long Excursion to Lydford and Brent Tor, Devon. *Proc. Geol. Ass., Lond.*, **34**, 32–8.

The Centenary Reunion

10 November 1958

THIS PART of our Centenary Celebrations was held in the Apartments of the Royal Society and the Geological Society of London, by courtesy of their respective Councils.

Over 530 members and friends were received by the President (Prof. D. Williams) and Mrs. Williams. The usual ordinary meeting of the Association was held, after which discussion centred informally in groups, around the exhibits or the licensed buffet.

The thanks of the Association are due to all those who made the evening the success it undoubtedly was, whether by attending, exhibiting or organising.

F. H. M.
D. W.

LIST OF EXHIBITS

British Museum (Natural History)

Department of Mineralogy

(*a*) Mineralogy and Petrology in the middle of the nineteenth century.

Department of Palaeontology

(*a*) Methods of supporting specimens during chemical development (A. E. Rixon).
(*b*) (1) The work of James Lyon Widger, 1823–92, the first excavator of the Tor Bryan Caves, Devon.
  (2) Recent discoveries of remains of Lynx from caves in S. Devon (Dr. A. J. Sutcliffe).
(*c*) The brains of dinosaurs (Dr. W. E. Swinton).

Directorate of Overseas Geological Surveys

(*a*) Some recent aerial photographs of Mt. Ruwenzori, Uganda.
(*b*) Some unusual rocks from Tanganyika.

Geological Survey and Museum

(*a*) Microscopic and radiographic investigations of Mesozoic ironstones.
(*b*) New Museum exhibits of lead and zinc ores.
(*c*) A new technique for the identification of ore minerals.
(*d*) A survey of ground-water resources.
(*e*) Geophysical surveys.
(*f*) Fossils from the London–Yorkshire Motorway.
(*g*) Recently published geological maps.

Geological Survey of New Zealand

The work of the New Zealand Geological Survey.

Nature Conservancy, The

The Geological Work of the Nature Conservancy (Dr. W. A. Macfadyen).

Imperial College of Science and Technology

(*a*) Ore textures (Prof. D. Williams).
(*b*) (1) Tintagel Haven, 1868, by Alfred Harris (Dr. Gilbert Wilson).
(2) A geological intersector, by Prof. John Phillip, 1836.
(*c*) An early geological map (D. J. Shearman).
(*d*) Field maps of parts of the NW. Highlands of Scotland and specimens illustrating the structural geology (Prof. J. Sutton, Dr. J. Ramsay and post-graduate students).
(*e*) Zeolites from Iceland and Antrim (Dr. G. P. L. Walker).

Kingston Technical College

Specimens from Assynt and Ardnamurchan, collected on 1950–8 field classes (D. Whitten, G. T. Raine and students).

Leicester University

(*a*) Geology of the area around Leintwardine, Shropshire (J. H. McD. Whitaker).
(*b*) Pre-Cambrian fossils from Charnwood Forest (T. D. Ford).
(*c*) Geology of the Haliburton–Bancroft area, Ontario, Canada (A. M. Evans).

The Association

Our First Century:
(*a*) Photographs (Mrs. M. W. Carreck).
(*b*) Publications (E. E. S. Brown).

Blezard, R. G.

Fossil Assemblage of the West Thurrock Chalk (*M. coranguinum* Zone).

Bottley, Mr. and Mrs. E. P.

(1) Fossil plant slides from the original Lomax collections.
(2) Fine specimens of English minerals.
(3) New geological models.
(4) New direct reading specific gravity balance for use in the field.

Bowes, Dr. D. R.
(*a*) The Lugar Sill.
(*b*) Concentrically basified boulders from Broken Hill, N.S.W.

Brown, E. E. S.
Eoliths collected by the late Benjamin Harrison.

Carreck, J. N. and Mrs. M. W. Carreck
The Abbotsbury iron ore.

Carreck, J. N., Mrs. M. W. Carreck and M. P. Kerney
The Early Holocene Tufa of Blashenwell, near Corfe Castle, Dorset.

Carreck, Mrs. M. W. and Mrs. J. V. Fifer (Churchdown County Secondary School for Girls, Bromley, Kent)
The Geological History of the Isle of Wight based on field work by girls aged 13–14.

Chubb, Dr. L. J.
Nineteenth-century geologists in the West Indies.

Collins, J.
Introduction to a classification of the invertebrates.

Elliott, G. F.
'Sow.' & 'D'orb.'.

Elwell, R. W. D., R. R. Skelhorn and A. R. Drysdall
Inclined granitic pipes in Guernsey.

Gunner, A.
Victorian chalk fossils and their display, from the Willett Collection.

Hollingworth, Prof. S. E.
A geological map of the area between Svartisen and Beiartind, N. Norway.

Kirkaldy, Dr. J. F.
The work of the Weald Research Committee.

Montford, H. M.
Gardner's map of England and Wales, 1826.

Patchin, B. G.
Fluorescence of calcites.

Pitcher, Dr. W. S. and Prof. R. M. Shackleton
The Islay Boulder Bed in Ireland.

Sayers, C. F.
A novel type of saw for the economic slitting of quartz crystals, etc.

Schnellmann, Dr. G. A.
A geological map of Iran.

Spencer, H. E. P.
Man and the Red Crag.

Stebbing, W. P. D.
Nephrite from New Zealand, the 'Dudley Locust' and tooth from 'Giant Shark'.

Stinton, F. C.
Otoliths as indices to Tertiary fish faunas.

Torrens, H. S. (Sherborne School Natural History Society)
Fossils from the Yeovil Sands of the Sherborne Area.

Wright, C. W.
A quarter of a century collecting in the Cretaceous.

Wyley, J. F.
Gastroliths from the Weald Clay of Ockley, Surrey.

Wymer, J. and Mr. and Mrs. B. O. Wymer
The Swanscombe excavations, 1958.

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